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Leaky-Wave Structures and Techniques for Integrated Front-End Antenna Systems

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ABSTRACT Leaky-wave antenna (LWA), as a special kind of waveguiding structure simultaneously characterized by both the guidance and radiation of electromagnetic waves along it, has received much attention and has been in the spotlight of both academia and industry since its inception in the 1940s. This is mainly because LWAs possess many appealing properties such as the highly directive beam, easy feeding mechanism, simple configuration, and particular frequency-driven beam-scanning, which enable them to hold promise in the development of a unique front-end antenna solution than others (e.g., reflector antenna and phased array). In addition to these inherent features, the exploitation of LWAs featuring multifarious sophisticated electrical functionalities (i.e., functional LWAs), with resort to engineering relevant radiating discontinuities and waveguiding structures, constitutes one mainstream research in the communities and increasingly prevails in the research & development of modern multifunctional wireless RF/microwave systems recently. This article is structured under this background, which is mainly dedicated to reviewing and investigating several enabling concepts, structures, and techniques that are specifically applied to the design of functional LWAs characterized by, for example, simultaneously low side-lobe and cross-polarization behaviors, rapid beam-scanning, stable radiation, frequency-selectivity, and open-stopband suppression. To make the technical discussions much more self-contained and systematic, this article begins with leaky-wave basics as well as general geometrical and electrical characteristics of LWAs. In addition, some representative system-level applications enabled by LWAs are briefly described, together with several promising research directions that can be further explored and galvanized, from the authors' perspective.

INDEX TERMS MTT 70th Anniversary Special Issue, antenna engineering, antenna front-end systems, beam-scanning, filtering antenna, functionality, frequency-selectivity, frequency-scanning system, guided-wave structures, leaky waves, leaky-wave antenna (LWA), leaky-wave structure, low side-lobe, low cross-polarization, multifunctionality, periodic structures, open-stopband, radar, radiating discontinuity, rapid beam-scanning, stable radiation.

I. INTRODUCTION

Before our formal descriptions and discussions of leaky-wave antennas (LWAs) in this article, it is interesting and inspiring to imagine a very common scene in our daily lives: in a golden summer and after a wonderful dinner, you walk your dog passing through a garden or grassland, and you may usually notice that there is often a lawn sprinkler or irrigation device consisting of a set of water-leaking pipes that are working automatically. Each pipe is drilled with a series of small holes through which the water can flow along the pipe while simultaneously spraying out for watering purposes, as pictured in Figure 1. An LWA, interestingly speaking, is just like a special "water-leaking pipe" to some extent if one perceives the electromagnetic (EM) energy and leaky waveguiding structures in the RF/microwave world as the water and pipes in such irrigation systems, accordingly. Just as the role of those holes that are indispensable to enable a pipe to spray water out, the radiating discontinuities (RDs), which

FIGURE 1. A daily-life example used to intuitively but not rigorously illustrate and understand LWAs: water-leaking pipes in a lawn sprinkler [1] (royalty-free image).

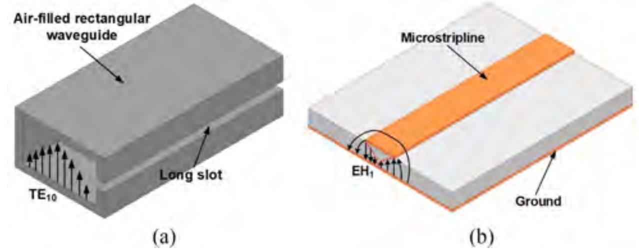

FIGURE 2. Two milestone-marked examples of LWAs. (a) Air-filled rectangular waveguide with a continuous long slot/slit cut along its sidewall (the first LWA, in the history of leaky-wave developments, invented by W. W. Hansen in 1940 [10]). (b) EH_1-mode microstrip-line LWA (the first printed uniform microstrip-line LWA, invented by W. Menzel in 1978 [11] and explicitly explained by A. A. Oliner in 1986 [12]). The two LWAs are representatives of uniform-type LWAs.

may be distributed continuously or discretely along the host waveguiding structures, play a similar role in LWAs. They act as coupling windows for the EM waves flowing along waveguiding structures to be coupled to the outside free space. Resultantly, the relevant guided mode is transformed into a leaky mode and thus radiation occurs. That is why we name the "antenna" to such a leaky waveguiding structure, implying its "radiation" functionality.

Although the last paragraph has provided a vivid example for us to intuitively understand LWAs, attention should be paid that it is not rigorous in physics since the leaking water along a pipe illustrated in Figure 1 is not a "wave" and thus does not have the wave interference effects (constructive or destructive) that the EM energy in a practical leaky-wave structure does have. Nevertheless, it is believed that this metaphor or analogy can be easily accepted by novices who just step into our leaky-wave territory. Strictly speaking, an LWA is a special form of waveguiding structure along which a traveling wave propagates while simultaneously leaking/radiating power to outer free space, usually accompanied by a frequency-scanned radiation beam [2], [3], [4], [5], [6], [7], [8], [9]. Also, an LWA can be regarded as a series-fed traveling-wave antenna array where the feeding line (host waveguiding structure) and antenna elements (RDs) are naturally and seamlessly integrated [6]. Note that in this case, the antenna elements or RDs may be continuously or discretely distributed along the host waveguiding structure as mentioned before, upon which LWAs can be, in general, topologically classified into uniform, quasi-uniform, and periodic types, as will be described later. Alternatively, LWAs can be interpreted and analyzed as a class of artificial or equivalent lossy transmission lines (TLs) where the desired radiation leakage manifests the transmission loss (dissipation losses from conductors and dielectrics are not considered here).

The earliest example of LWAs can date back to 1940, appearing in a patent and invented by W. W. Hansen [10]. It is based on an air-filled rectangular waveguide (RWG) where a continuous long slit (or slot) is cut along its sidewall, as sketched in Figure 2(a). The EM energy carried by the RWG is progressively leaked out or coupled to the outside free space through the slit when the perturbed TE_{10} modal fields propagate. The radiation leakage occurs over the length of the slit, and the whole slit length, in general, constitutes an effective radiating aperture. Notably, because of the slit and EM power leakage, the original boundary condition of the RWG is destroyed, and its initial purely real Eigen solutions or propagation constants (without considering any dissipation losses) of the guided mode are changed to some extent. Complex propagation constants, including phase constant β and attenuation constant α, are formulated with the newly formed boundary condition in a certain frequency range. In this case, the original purely bound guided mode becomes a leaky mode responsible for the radiation mechanism. As a side note, using a natural leaky mode, which individually satisfies the boundary conditions of relevant leaky-wave structures just like the cases of the slitted RWG described above and the EH_1-mode microstrip [11] shown in Figure 2(b), merely constitutes one of two typical methods to create leaky-wave radiation. Space-harmonics (also called "Floquet modes"), which are related to periodic structures, can also be used alternatively to yield leaky-wave radiation. Of course, there must be some similarities and differences between the two types of leaky "modes", which make related LWAs present different geometrical and electrical behaviors, as will be detailed in the next section.

Before designing an LWA, its complex propagation constants should be comprehensively studied and accurately calculated. This is because such two transmission-type parameters are critical for determining the LWA's electrical properties such as the main-beam direction, beam-scanning rate, beamwidth, radiation efficiency, side-lobe level (SLL), impedance/radiation bandwidth, etc. [2], [3], [4], [5], [6], [7], [8], [9]. For example, an LWA with a larger leakage attenuation constant α is prone to produce a shorter antenna aperture and more sharply tapered amplitude distribution, resulting in a wider radiation beam, lower directivity, and unsatisfactory SLL. Indeed, it is well recognized that if such transmission-type parameters (i.e., α and β) can be flexibly engineered for an LWA, its main circuit/radiation features can be tailored accordingly, paving the way for designing LWAs with different electrical functionalities and capabilities. To this end, one may resort to making efforts on the host waveguiding structures

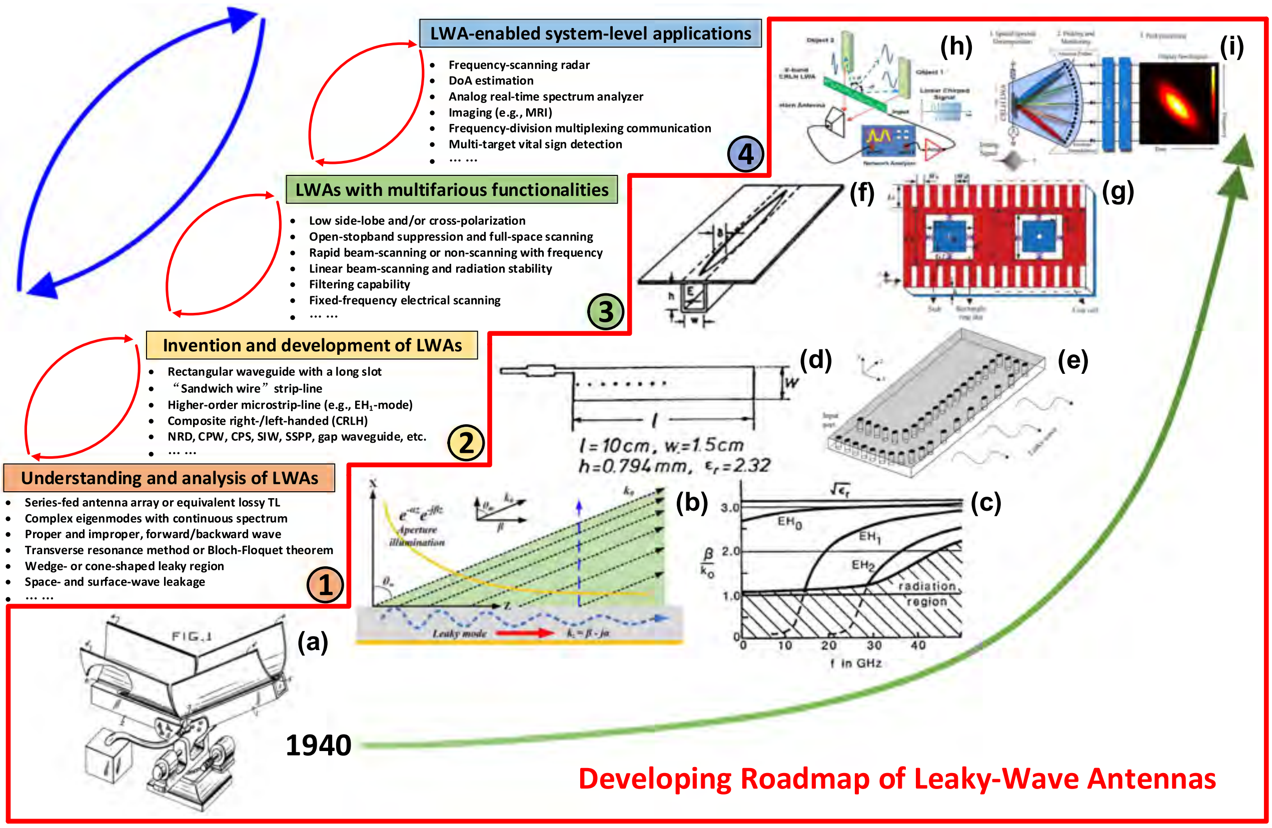

FIGURE 3. An overview diagram illustrating the four-stage developing roadmap of LWAs since 1940. (a) The first known LWA in history [10]; (b) Near-field ray illustration of a forward "improper" leaky mode [2], [3]; (c) Dispersion diagram of a microstrip-line illustrating the space- and surface-wave leakage [12] (©1986 IEEE); (d) The first known EH1-mode microstrip-line LWA [11] (©2007 IEEE); (e) The first known SIW-based LWA [21] (©2005 IEEE); (f) Tapered long-slot RWG LWA with low SLL performance [22] (©1953 IEEE); (g) Fixed-frequency electronically scanned LWA based on the corrugated SIW [23] (©2019 IEEE); (h) DoA estimation system [24] (©2015 IEEE); (i) Analog real-time spectrum analyzer [25] (©2009 IEEE). All these figures are reproduced or adapted with permission. This article is more focused on the third stage while the other three are just briefly discussed.

and/or RDs, which coordinately constitute two main means to engineer such two parameters of LWAs, as will be explicitly exemplified later in this article. Note that RDs also have a direct impact on some critical radiation properties of LWAs, such as the possibility of radiating towards the end-fire direction [13], [14], [15], [16] or with low cross-polarization level (CPL) [17], [18], [19], [20] according to the antenna array theory. In short, this natural "hybrid" radiating-while-guiding characteristics of LWAs (i.e., a hybrid inherited from both antennas and waveguiding structures) makes them attractive over many decades and still sparkle to date.

Although it was just such a simple cut made on an ordinary RWG in 1940, this seemingly unimpressive action profoundly kindles a great research enthusiasm in leaky-wave phenomena, physics, and theories, and in constructing and analyzing various LWAs in the remaining days of the last century. The past several decades have seen a lot of pioneers who joined the rank and made significant contributions to this field, such as A. A. Oliner, N. Marcuvitz, T. Tamir, W. Menzel, D. R. Jackson, and Paolo Lampariello, just to name a few. From the authors' perspective, the developing roadmap of LWAs when looking back over the years can be essentially divided into four stages, as structured in Figure 3. There is no strict chronological order among these development stages (more generally, a spiral or rotary evolvement pattern can be observed between these stages). For example, it is seen that comprehensive analysis activities exploring leaky-wave physics were conducted after the invention of the first LWA in 1940 [10]; this is also the situation of research interests and efforts observed in communities after the higher-order-mode printed-type LWA (i.e., microstrip) was proposed in 1978 [11]. However, when looking reversely, it is found that an explicit and in-depth understanding and exploration of leaky waves have inspired the development and invention of more kinds of LWAs, among which Fabry-Perot cavity antennas or partially reflective surfaces [26], [27], [28] are explained and recognized as LWAs while some other new concepts such as leaky lens [29], [30] and metasurfaces (guided-wave-fed) [31], [32], [33] are also devised and integrated into our leaky-wave communities nowadays. Another apparent fact manifesting the evolvement pattern of Figure 3 is that currently existing wireless systems such as frequency-scanning radars normally stipulate what electrical performances or functionalities should be embraced by LWAs (e.g., low SLL, low CPL, radiation stabilities, etc.), while the invention of novel functional LWAs or the innovative use of LWAs can trigger and bring fresh system-level applications to communities like the composite right-/left-handed (CRLH) LWA-enabled direction-of-arrival (DoA) estimator [24] and analog spectrum analyzer [25], and the frequency-division multiplexing (FDM) communications [34]. In retrospect of the development of the leaky-wave community, it is undoubtedly recognized that the leaky-wave phenomena, physics, and theories had been well explored and divulgated in the last century thanks to the efforts made by those pioneers [2], [3], [4], [5], [6], [7], [8], [9], such as the knowledge of the continuous spectrum nature of complex eigenmodes presented by a leaky wave, the "proper" and "improper" nature of forward and backward leaky-waves, respectively, the "wedge-shaped" leakage region defined close to the leaky-wave structure, and the "spectral gap" in the transition region from a fast-wave leaky mode to a slow-wave guided mode. At the same time, it is also a consensus that a wide variety of LWAs can easily be developed as long as the aforementioned radiation mechanisms of two types of leaky "modes", which pertain to uniform and periodic LWAs, are kept in mind in the initial design process. Currently, there are almost no big problems in understanding leaky-wave physics and creating leaky-wave radiation using various waveguiding technologies and RDs. Instead, we are more concerned with how to design and develop LWAs with promising functionalities or electrical behaviors, e.g., low SLL, low CPL, stable radiation, rapid beam-scanning, etc., most of which are largely required for practical front-end antenna systems in wireless communications and radars. For example, we will discuss later several works to realize LWAs with both low SLL and CPL performance, since a non-tapered LWA naturally suffers from a high side-lobe of about −13−dB (which is insufficient for modern radar or other wireless applications) [2], [3] while inappropriate tapering techniques may spoil or deteriorate the CPL behavior [17], [18]. Besides, we also hope an LWA can provide a continuous and smooth beam-scanning capability from backward to forward quadrants passing through the broadside direction, which is very practical for radar-related applications requiring a large field-of-view (FoV) coverage. This usually resorts to using periodic LWAs unless the inherent "open-stopband" trouble can be effectively tackled [3], [5], [7]. Furthermore, since an LWA's beam is scanned with frequency, it would be desired in some applications, such as the fast-tracking radars [35], [36], if a larger FoV can be covered by paying less spectral resources. This implies that the rapid beam-scanning behavior should be embraced by LWAs. Note that the electrical stabilities in terms of several radiation-related parameters such as efficiency, gain, and beamwidth are generally needed for a frequency-scanned beam in practical LWA-enabled systems, not to mention that developing LWAs simultaneously possessing other functionalities or even multi-functionalities (e.g., rapid beam-scanning and filtering characteristics) will be of particular interest for developing promising front-end

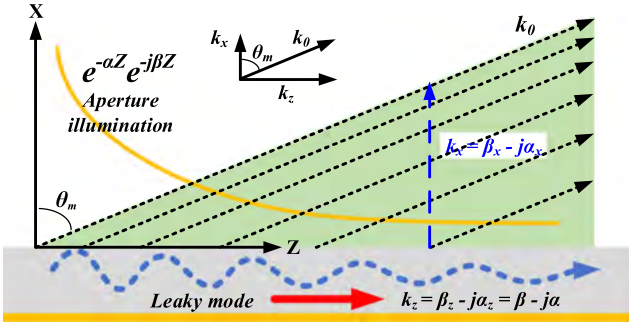

FIGURE 4. Near-field ray illustration of a forward leaky mode ("improper") propagating along a grounded substrate in the +Z direction [2], [3]. EM power progressively leaks out to the free space when the leaky mode propagates forwardly.

antenna systems in R&D communities. This is the main purpose of this article, which aims to provide an overview of the design and development of such functional LWAs. We try to analyze and disclose their related enabling concepts, structures, and techniques from the perspectives of "waveguiding structure" and/or "RD", as will be elaborated on Section III. In addition, leaky-wave basics and generalities of LWAs, together with LWA-enabled system-level applications, are briefly described to make this article relatively self-contained; they are arranged in Sections II and IV, respectively. Further research efforts and directions in LWAs are also speculated from the authors' viewpoint at the end of this article (i.e., Section V). If not otherwise specified, all the LWAs and their related waveguiding structures mentioned in this article are considered one-dimensional (1-D) by default.

II. FUNDAMENTALS OF LEAKY-WAVE ANTENNAS

A. LEAKY WAVES: FROM PHYSICAL NATURE TO RADIATION FEATURE

The class of leaky waves represents a very important and basic type of waves in addition to the plane wave in an infinite free space and the guided wave in a bound region. They are a sort of complex plane waves characterized by a complex wavenumber even though the propagation medium may be considered completely lossless. The "complex" nature of the leaky wave or mode inside a propagation space (e.g., waveguide/TL) is attributed to a continuous EM power leakage to its neighbor propagation space (e.g., free space) when the original wave is propagating along the related interface. Figure 4 illustrates a leaky mode propagating in the +Z direction, where there is a progressive power leakage from the grounded substrate to the free space. The amplitude or power of the leaky mode continuously decreases with its phase being progressively delayed when the leaky mode moves forwardly along the length (a forward wave with positive attenuation and phase constants, i.e., $\alpha_Z > 0$ and $\beta_Z > 0$). Whereas general guided modes present a purely real propagation wavenumber and are modal solutions (or eigenvalues) of the Maxwell equations under specific boundary conditions, those leaky modes, normally, are also modal solutions while distinctively presenting complex eigenvalues and thus being "improper" mathematically [2], [3]. The so-called "improper" is because the amplitude of leaky waves would exhibit, at first glance, an increasing or "amplifying" trend when running away from the leaky-wave structure, mathematically manifesting a positive phase constant but a negative attenuation constant in the transverse +X direction (i.e., $\alpha_x < 0$ and $\beta_x > 0$), as observed along the blue arrow-headed dash-line in Figure 4. This feature of leaky waves sharply contrasts with that of guided waves, which behave in a "proper" manner—their field amplitudes decrease transversely (i.e., transversely bounded or trapped) such that normal EM power guidance is allowed longitudinally. Despite such "improper" characteristics, leaky waves are physically existent and can be measured, because, in practice, they are defined only in a "wedge-shaped" near-field region close to the interface of a leaky-wave structure and never reaches the transverse infinity [2], [3]. This phenomenon can be observed in Figure 4 in that the field intensity only shows an increasing trend until reaching the boundary of the wedge-shaped (greenish) leakage region, i.e., $Z\cot(\theta_m)$. Notably, a "proper" propagating leaky mode that attenuates transversely ($\alpha_x > 0$ and $\beta_x > 0$) certainly exists for a backward wave whose phase is progressively advanced when propagating forwardly ($\alpha_z > 0$ and $\beta_z < 0$). As a side note, compared to forward leaky waves that produce a beam generally scanned from the broadside towards end-fire directions in the forward quadrant, backward leaky waves possess the opposite situation [3], [5]. Namely, they have a radiation beam oriented towards the backward quadrant and scanned from the backfire to broadside directions. These dissimilar beam-scanning behaviors related to forward and backward leaky waves are closely linked to different LWA types such as uniform, quasi-uniform, and periodic LWAs, as will be described later.

The leaky-wave phenomenon may occur when a propagating wave along a medium has a phase velocity that is faster than that of a wave propagating in the neighbor medium (i.e., the so-called "fast-wave" condition), provided that the interface between the two media is unshielded. For example, as illustrated in Figure 2(a), although the phase velocity of the dominant TE_{10} mode inside an air-filled RWG is faster than the light speed of the neighboring free space, there would be no leaky waves existing unless a physical cut is introduced to interconnect such two propagation spaces. On the other hand, for an open waveguide that is already electromagnetically transparent to its neighboring space and whose dominant mode is a radiation-less bound mode (slow-wave in nature) that does not radiate, radiation leakage can still be obtained. For instance, as summarized in [2], [3], [4], we can (i) introduce some asymmetries to change the slow-wave bound mode into a fast-wave leaky one, (ii) use a higher-order mode that has a fast-wave frequency region like that in Figure 2(b), or (iii) periodically modulate the slow-wave open waveguide to generate an infinite set of space-harmonics in which one or more of them with fast-wave behavior may present power leakage. In either case, a leaky wave will then be excited along the waveguiding structure, contributing to aperture fields on the interface from which radiation can take place. The relevant far-field radiation pattern can be easily estimated by taking a Fourier transform of the aperture fields. Consequently, one may find that the details of a leaky wave, which has a physical definition in the near field only of leaky-wave structures, will determine their far-field radiation properties.

In general, the far-field radiation of an LWA is mainly characterized by three parameters: the main-beam direction, the 3-dB beamwidth, and the SLL. For a non-tapered LWA, its phase and attenuation constants (β and α) will be kept constant along its length. In this case, the aperture field illumination can be characterized by a line source whose mathematical expression shares the same exponential factor as the leaky mode inside the LWA. The relevant radiation main-beam direction θ_m is expressed as[1]

$$\sin(\theta_m) \approx \frac{k_z}{k_0} \approx \frac{\beta}{k_0} \tag{1}$$

where θ_m is measured from the broadside direction (the direction perpendicular to the leaky aperture) while k_0 denotes the free space wavenumber [2], [3]. β may represent the phase constant of the natural leaky mode of a uniform LWA; it can also denote the counterpart of a radiating space-harmonic in periodic-loading-based LWAs, i.e., quasi-uniform and periodic LWAs. As a side note, (1) speculates that a real-valued main-beam direction θ_m (i.e., the beam's maximum lies in a visible region) only exists on the premise that the absolute value of the phase constant of the leaky "mode" is not larger than the free space wavenumber. This equation also mathematically explains why the leaky-wave phenomenon generally necessitates a fast-wave condition, where the so-called "fast-wave" herein is especially compared to the light speed in the free space (vacuum or air) surrounding general LWAs [37], i.e., *superluminal* propagation. On the other hand, let's recall that the attenuation constant α is a measure of the power leaking away per-unit-length along the LWA. That is to say, if α is small, the effective aperture length of the LWA would be large (we assume that the physical length of the LWA is long enough), and resultantly its far-field radiation pattern would present a narrow beamwidth. Basically, for a finite leaky aperture with a fixed length of L, its radiation efficiency e_r is determined by the attenuation constant α, which can be expressed as

$$e_r \approx 1 - e^{-2\alpha L} \tag{2}$$

If we assume that 90% of the injected power is leaked away before reaching the termination end where the remaining power would be absorbed, the 3-dB beamwidth of LWAs can be formulated as

$$\Delta\theta_{3dB} \approx 5\frac{\alpha/k_0}{\cos(\theta_m)} \tag{3}$$

[1]The first approximation involved in (1), i.e., the left-sided one, is due to the fact for a general LWA, its far-field main-beam direction is almost the same as the angle-of-leakage of the EM power in the near-field. Comparatively, the second approximation (right-sided one) made in (1) considers the fact that the attenuation constant α, compared to the phase constant β, is generally very small and therefore is normally omitted without loss of generality.

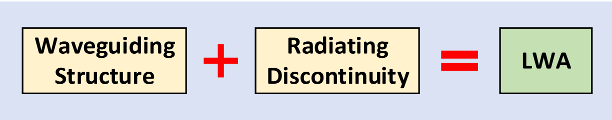

FIGURE 5. A special formula describing the general construction principle of an LWA. Comprehensive classifications of LWAs can be made in reference to the two anatomical items on the left of the formula.

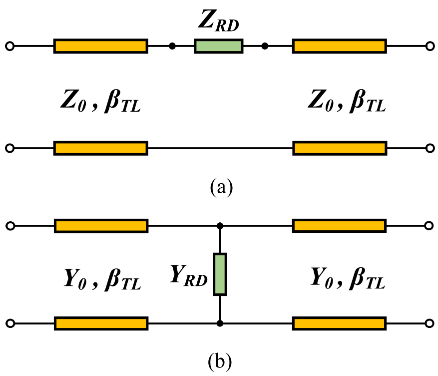

FIGURE 6. Two fundamental equivalent TL circuit models of an LWA with respect to how to electromagnetically load RDs on host TLs/waveguiding structures. (a) Series-loading type. (b) Shunt-loading type. Z_0/Y_0 is referred to as the characteristic (or Bloch) impedance/admittance of the host TL, while β_{TL} represents the phase constant (or effective one) of the host TL. Z_{RD}/Y_{RD} denotes the impedance/admittance of the loaded RD. The loaded RDs are arbitrary and may be physically embodied as a simple or composite radiator while being electromagnetically characterized by an SMR (single-mode resonator) or MMR (multimode resonator). More complex equivalent TL circuit models, together with diversified RDs, can be constructed in principle depending on practical LWAs.

Apparently, it can be seen that both the radiation efficiency and radiation beamwidth are closely related to the attenuation constant α.

B. OVERVIEW OF LEAKY-WAVE ANTENNAS

The aforementioned two prerequisites for leaky-wave radiation [2], [3], [37], i.e., “fast-wave” and unshielded interfaces, are closely connected to the host waveguiding structures and RDs employed in LWAs, as shown in Figure 5, which depicts a special formula demonstrating a general construction principle of LWAs. It can be said that the development of almost any LWA follows this scheme. Comprehensive classifications of LWAs can be made by observing the two items on the left side of this formula, upon which *three* major criteria can be identified for systematic classification purposes. For example, depending on the way of how distributing/loading RDs on waveguiding structures, LWAs can be topologically classified into uniform, quasi-uniform, and periodic types, or electromagnetically sorted into series- and shunt-loading types with respect to the equivalent TL circuit models as illustrated in Figure 6. Besides, we can also separately classify LWAs according to waveguiding techniques and resonance characteristics of RDs, as will be detailed later.

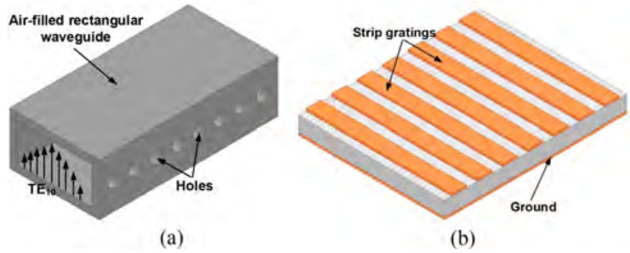

FIGURE 7. Two representatives illustrating quasi-uniform and periodic LWA classes [2], [3]. (a) Quasi-uniform LWA, where an air-filled rectangular waveguide with densely spaced holes drilled on its sidewall is illustrated. (b) Periodic LWA, where a grounded dielectric slab with an array of strip gratings printed on its top is illustrated. The radiating fast-wave leaky “modes” in (a) and (b) are typically the fundamental and -1st-order space-harmonics, respectively. Over the working frequencies, the periodicity of loadings is less than a half-wavelength in (a) whereas is in an order of a wavelength in (b).

1). UNIFORM, QUASI-UNIFORM, AND PERIODIC—THE WAY OF TOPOLOGICALLY DISTRIBUTING RDS ON WAVEGUIDING STRUCTURES

The uniform type LWA is one whose cross-section is kept unvaried along the wave propagation direction. The relevant RDs are distributed continuously along the structure, while the radiation mechanism is due to a natural fast-wave leaky mode (the one satisfying the Maxwell equations and boundary conditions). Several typical examples fall into this LWA group, and perhaps the best-known two are the slitted air-filled RWG and the EH_1 mode microstrip-line LWAs shown in Figures 2(a) and (b), respectively. Comparatively, quasi-uniform LWAs can be interpreted as a special class of “uniform” LWAs since such two classes of LWAs have similar radiation features even though they have quite different geometrical appearances. Indeed, the quasi-uniform LWA has a periodic appearance that resembles the periodic type of LWA, as shown in Figures 7(a) and (b) where two representatives of such two types are exemplified, respectively. Although periodic perturbations or loadings in a quasi-uniform LWA will introduce an infinite number of space-harmonics, the periodicity is small enough such that the frequency effects of those higher-order space-harmonics are marginal over the working frequency band of interest. Consequently, it is still the fundamental space-harmonic that is responsible for the radiation mechanism. Consider the fact that the fundamental space-harmonic of a quasi-uniform LWA is just a slightly perturbed guided mode of the related host waveguiding structure, while the leaky-wave radiation needs the working leaky “mode” to be in the fast-wave region. The quasi-uniform LWA’s host waveguiding structure, therefore, should be capable of providing a natural fast-wave guided mode, which is similar to the previous uniform type LWA in this aspect. Also, note that most typical quasi-uniform and uniform LWAs can only provide a forward beam-scanning from the broadside towards end-fire directions because only forward leaky waves are supported propagating along them.

The periodic LWA is normally defined as one that has a periodicity in an order of a guided wavelength. A unit-cell length of one or more guided wavelengths, corresponding to the first- or higher-order space-harmonics, are employed for the radiation mechanism. For this kind of LWA, the original guided mode of the host waveguiding structure always exhibits a slow wave in nature (again, in the working frequency region of interest) for which there is no radiation leakage occurring when waves propagate along it. Actually, according to the traditional antenna array theory, one can perceive that there is "radiation" occurring in such a slow-wave structure while unfortunately the main beam is moved into an invisible region (note that what we refer to here is a more general case and the Hansen-Woodyard super-directivity end-fire radiation is not involved) [37]. This corresponds to a complex value of the main-beam direction θ_m based on (1) as mentioned before. When RDs are periodically loaded onto the waveguiding structure, the propagating wave along the structure is in the form of a Bloch wave, which can be mathematically expressed as a traveling plane wave modulated by a spatial-domain periodic function [38]. In this context, this propagating Bloch wave can be expanded to an infinite number of space-harmonics according to the famous Fourier series, which is typical for a time-domain periodic signal. Although the fundamental space-harmonic is a slow wave in nature, some higher-order space-harmonics, usually the -1st-order, can be designed to be a fast-wave radiating leaky "mode". The Bloch-Floquet theorem [38] can be conveniently used to analyze this kind of LWA and extract the complex propagation constants of space-harmonics. Accordingly, the phase constant of the nth-order space-harmonic, β_n, can be expressed as [2], [3], [38]

$$\beta_n = \beta_0 + \frac{2n\pi}{P} \tag{4}$$

where P denotes the period length of the unit-cell. β_0 represents the phase constant of the fundamental space-harmonic, which stems from that of the host waveguiding structure's guided mode while presenting a little difference caused by RDs' perturbation or loading effects. To predict the relevant main-beam direction of periodic (or quasi-uniform) LWAs, (1) can be used herein provided that the radiating space harmonics' phase constant is substituted in the numerator accordingly. Notably, compared to uniform and quasi-uniform LWAs, periodic LWAs' radiating space-harmonics behave as backward and forward leaky waves with frequency. Thus, they have the potential of providing a full-space beam-scanning from backward to forward through broadside direction, provided that some special measures would be implemented to overcome the notorious "open-stopband" effects [2], [3]. Another discussion that pertains to the three types of LWAs will be described in Section III-D.

2). WAVEGUIDING STRUCTURE—THE PHYSICAL BODY IN SUPPORT OF LEAKY WAVES

Since the construction of LWAs inevitably depends on waveguiding structures, as illustrated in Figure 5, LWAs can be accordingly classified in reference to different waveguiding techniques, such as metallic waveguide [10], [17], [18], [22], [39], [40], [41], [42], [43], [44], [45], [46], [47], microstrip-line [11], [12], [48], [49], [50], [51], [52], [53], [54], [55], [56], hybrid waveguide-planar technology [57], [58], [59], [60], co-planar stripline (CPS) [61], [62], [63], [64], [65], coplanar waveguide (CPW) [66], [67], substrate integrated waveguide (SIW) [13], [14], [19], [20], [21], [23], [68], [69], [70], [71], [72], [73], [74], [75], [76], [77], [78], [80], [81], [82], [83], [84], [85], [86], [87], [88], [89], [90], Goubau-line/spoof surface plasmon polariton (SSPP) [91], [92], [93], [94], [95], [96], [97], [98], [99], [100], [101], and gap waveguide [102], [103], [104], [105], [106], [107]. Notably, most waveguiding structures mentioned above can be viewed as "primitive" transmission solutions because they can be properly exploited as a basis for further devising "secondhand" (or "derivative") waveguides/TLs. For example, artificially synthesized or periodically loaded waveguides/TLs like CRLH TLs/LH waveguides [77], [78], [80], [108], [109], [110], [111], [112], [113], [114], [115] and periodic slow-wave structures [116], [117], [118], [119], [120], [121], [122], [123], [124], [125] can be constructed based on microstrip line [108], [117], [119], CPW [118], [120], [123], [124], metallic waveguide [111], [112], [113], [114], [115], and SIW [77], [78], [80], [121], [122], etc. Those "secondhand" or "derivative" TLs may be perceived as "equivalently primitive" ones in a broader sense, which can also be adopted as host waveguiding techniques for implementing LWAs (note that the SSPP, in fact, is a corrugated or periodically-loaded Goubau-line where the structural lattice is in a sub-wavelength manner, while the gap waveguide and the SIW, rigorously speaking, also follow a periodic topology). In this sense, the definition of "waveguiding structure" in Figure 5 for developing LWAs can be largely broadened.

The invention of different waveguiding structures has its own historical background and practical requirements, and, of course, each waveguiding technique has its specific technical features, benefits, and limitations. Consequently, selecting a waveguiding technique for developing LWAs depends on specific considerations such as cost, loss, fabrication complexity, power-handling capacity, integration level, etc. With the development of RF/microwave technologies, new waveguiding techniques are expected to be devised for suitable transmission and integration solutions. This is followed by relevant LWAs that are developed and adapted into new system platforms. For example, in the past two decades, the SIW [126], [127] has been demonstrated to be a brilliant waveguiding technique that combines the merits of the metallic waveguide and microstrip line in terms of loss, power-handling capacity, integration level, etc., upon which a large number of SIW-based LWAs have been proposed and developed for microwave/millimeter-wave applications. By contrast, recent years have witnessed a great research interest in the gap waveguide technology thanks to its benefits of low-loss and convenient fabrication/assembly at millimeter-wave frequencies [128], and in SSPPs (corrugated Goubau-lines) considering their low-loss and strong field-confinement features which may find great potentials in terahertz (THz) applications [129].

3). RADIATING DISCONTINUITY—THE COUPLING WINDOW OF EM POWER

Although LWAs, from a macroscopic perspective, are known as a class of non-resonant structures along which traveling waves propagate and leak out simultaneously, most RDs are usually comprised of resonant-type structures in which localized standing-wave phenomena (e.g., currents or fields) are presented from a microscopic point of view. Note that this remark is not fitted to uniform LWAs, since the relevant RDs like the long slot in Figure 2(a) or radiating edges in Figure 2(b) are generally characterized by a continuous geometrical distribution and non-resonant circuit behavior [4]. However, that remark can be well applicable to quasi-uniform and periodic LWAs in view of the fact that various discrete and resonant RDs are periodically loaded on them, which are used as the true radiation sources, i.e., coupling windows of EM power. For example, for waveguide/SIW-based LWAs, different types of resonant-type slots, e.g., transverse slot [13], longitudinal slot [85], and oblique slot [78], are etched on the waveguide surfaces (broad-wall or sidewall) to enable radiation leakage. For these waveguide/SIW slots, a half-wavelength resonance will usually take place at a certain frequency point [131], while slots in such a resonance status are typically used for developing standing-wave slotted antenna arrays for radar system applications [130], [132], [133]. Nevertheless, if LWAs are designed based on the slotted waveguides/SIWs, the dimensions of those slots should be deliberately selected such that their strong resonances do not intrude on the frequency band of leaky-wave operation. This is not only to ensure there will be no resonance-triggered bandstop occurring (this will be explained later in Section III-D) but to guarantee that a slowly attenuated leaky wave and thus a long antenna aperture can be formed, as usually required by LWAs for realizing a high directivity. All in all, it should be remarked herein that the RDs, to be more precise, are generally constituted by non-resonant structures in uniform LWAs, or resonant ones that are particularly tuned far from their resonance conditions in quasi-uniform and periodic LWAs.

Depending on specific waveguiding structures, there are a variety of available realization forms of RDs that can be exploited to develop LWAs. For example, slot apertures should be used in closed waveguides/SIWs as just described, while stubs can be exploited for microstrip type LWAs [50], [51], [52], [53]. Even composite-structure-based radiators such as the aperture-coupled patch and magneto-electric dipole antennas can be properly employed as RDs [84], [134]. Despite diversified RDs, their resonance characteristics are basically characterized by and can be grouped into single-mode-resonator (SMR) and multimode-resonator (MMR) over the frequency band of interest [134]. Therefore, it is reasonable in this case to reclassify LWAs into the two related families, namely, SMR- and MMR-based LWAs, as depicted in Figure 8. The SMR-based LWA is referred to as one where there is only a single strong resonance existing close to the frequency band of leaky-wave operation, i.e., the one that just uses a single resonance of the RDs within the frequency band of interest as depicted in Figure 9(a). Comparatively,

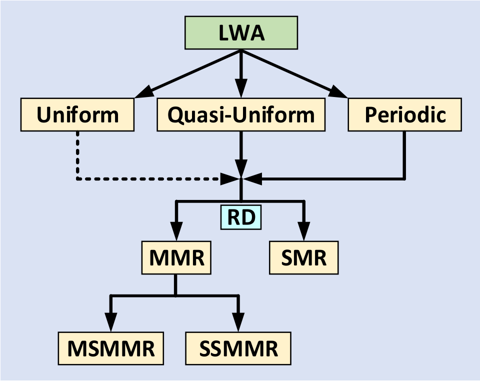

FIGURE 8. Reclassifying LWAs with an emphasis on RDs' resonance characteristics. SMR: single-mode resonator; MMR: multimode resonator; MSMMR: multi-structure MMR; SSMMR: single-structure MMR.

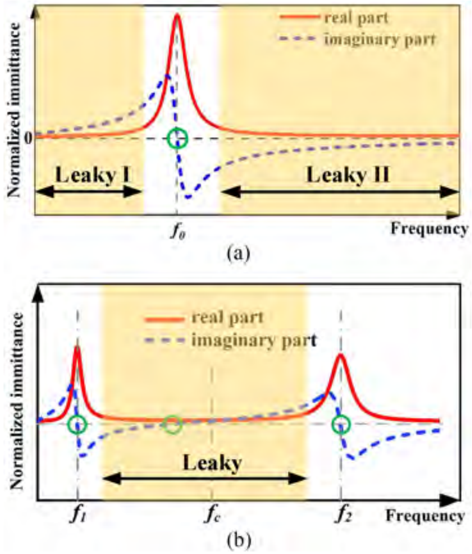

FIGURE 9. Normalized immittance properties of two basic kinds of RDs featuring different resonance characteristics [134]. (a) SMR-based RD. (b) MMR-based RD. Curve peaks in these figures, which will be referred to as "strong resonances" in the main text of this article, represent either shunt- or series-type resonances, corresponding to the impedance or admittance case, accordingly. Also, the impedance case applies to series-loading type RDs, while the admittance case is for shunt-loading counterparts, as pictured in Figure 6. Resonances are marked with green circles, while yellow-shadowed frequency regions represent ones that suit leaky-wave operation.

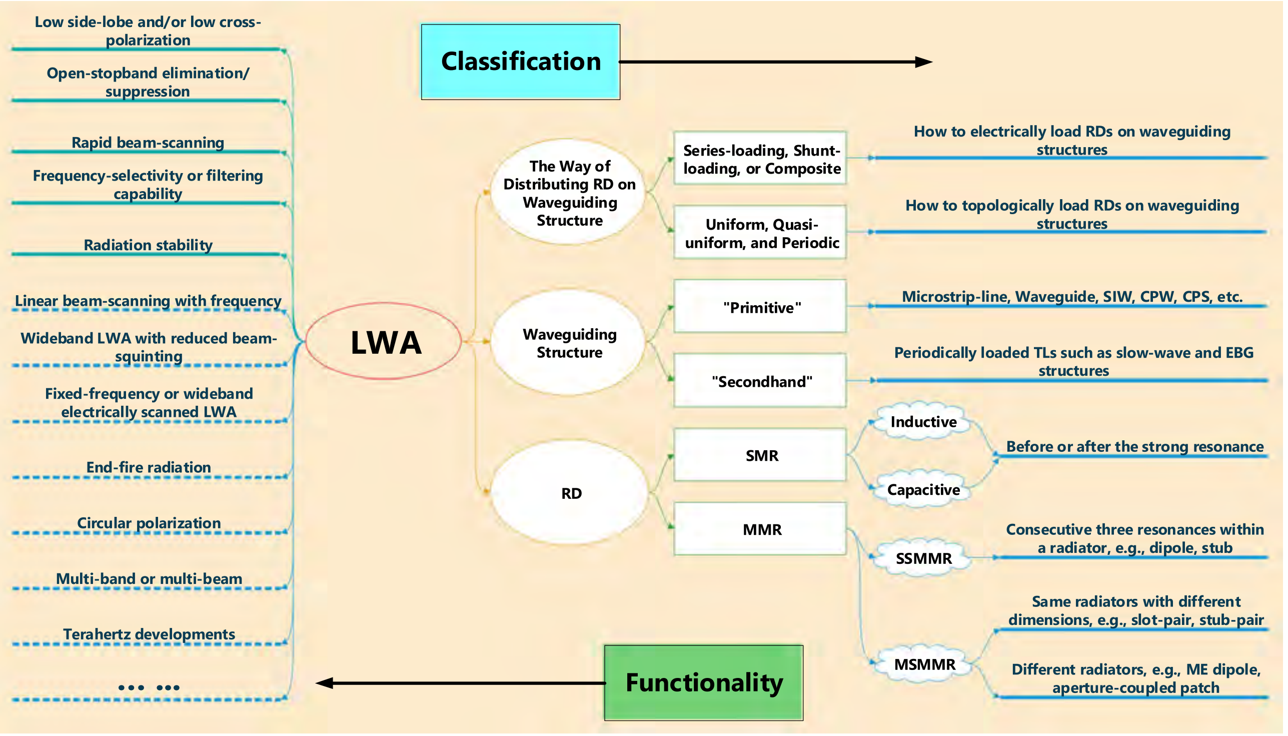

FIGURE 10. An anatomical diagram describing and summarizing various classifications and functionalities of LWAs. Only several of those functionalities are reviewed in this article.

the MMR-based counterpart takes advantage of multiple resonances simultaneously of the RDs, i.e., there are several strong resonances existing close to the frequency band of leaky-wave operation as illustrated in Figure 9(b). Generally speaking, this classification method mainly applies to quasi-uniform and periodic LWAs as explained before. Nevertheless, uniform LWAs may also loosely fall into this classification regime if one recognizes that their continuously distributed and non-resonant RDs are characterized by an SMR where the solo resonance is very far from the operating frequencies. Particularly, when focusing only on MMR-based LWAs, this family can be technically divided into two subgroups: multi-structure MMR (MSMMR) and single-structure MMR (SSMMR).[2] It is interesting to mention that the classification criterion of LWAs, from the perspective of RDs' resonance characteristics, can act as a bridge between the resonant antenna families and non-resonant-natured LWAs. Based on this, a large variety of wide-/multi-band resonant antennas can be borrowed and implemented directly on various waveguiding techniques (e.g., microstrip-line, CPS, CPS, SIW, etc.) for the design and development of MMR-based LWAs [130]. More details about MMR-based LWAs focusing on their features and benefits will be described later in Section III-E.

To facilitate general readers to understand the overview made on LWAs as described in this section, an anatomical diagram describing various classification criteria of LWAs, together with some functionalities as will be detailed next, is summarized in Figure 10. Although our treatments on LWAs in this section are focused on 1-D LWAs, 2-D LWAs [2], [3] can also be sorted, designed, and developed in a similar way. Typically, parallel-plate waveguides, dielectric slabs, and grounded dielectric slabs (or multi-layer stacked ones) are basic and representative waveguiding structures to construct 2-D LWAs provided that appropriate RDs such as slot apertures, patches, and strips are loaded (usually but not necessarily) [135], [136], [137], [138], [139], [140], [141], [142], [143], [144]. Different from general 1-D LWAs where the leaky waves propagate along a single direction resembling that the leaking water flows along a pipe illustrated in Figure 1, cylindrical leaky waves are formed and then guided *radically* on those 2-D waveguides as just mentioned. Recall that a fan-shaped broadside or dual-beam radiation can be realized depending on frequency when feeding a 1-D LWA at its center, thanks to the fact that two reversely orientated leaky waves are excited and then run in the opposite direction in this case [3], [7]. Such radiation characteristics of centrally-fed 1-D LWAs can be used to deduce the counterparts of 2-D LWAs in which a pencil beam or conical radiation pattern is obtained, accordingly. Both forward and backward leaky waves can also be supported in 2-D LWAs, resembling that

[2]Depending on the way of obtaining multi-resonance circuit behavior for an MMR-based RD, an MMR can be technically classified into MSMMR and SSMMR for convenient implementations. In detail, the MSMMR refers to the fact that multiple sub-structures are integrated together with each acting as a sub-resonator and contributing its own one or more resonances to the whole multi-resonance circuit behavior. By contrast, the SSMMR structure signifies that a single structure can provide multiple resonances in nature while all of them can be simultaneously used for designs. More details about such two subclasses of MMR-based RDs can be found in Section III-E.

of 1-D counterparts. Interesting readers may refer to [2], [3] for extended and in-depth theoretical studies of 2-D LWAs. Notably, in parallel to 1-D functional LWAs as focused on this article and will be detailed later, there are also a series of 2-D LWAs designed with various functionalities and capabilities existing in the open literature, such as Bessel beam generation, near-field focusing, holographic pattern synthesis, wideband pencil beam radiation, etc. These are summarized in [31], [32], [33] and will not be detailed hereinafter.

III. FUNCTIONAL LEAKY-WAVE ANTENNA ENGINEERING

How to understand the physical nature of leaky waves, and efficiently construct and accurately analyze LWAs based on different waveguiding structures and RDs have proved to be of significant interest in our research communities, especially in the early stages of leaky-wave history. Besides, there is one crucial aspect deserving attention during the development of LWAs: how to design desired electrical functionalities or capabilities for LWAs (the so-called "functional LWA engineering" in this section) so that they can perform well in current systems or even trigger new applications? This pragmatism has enticed a lot of research interests and efforts in developing functional LWAs. Considering that it is impossible to cover every class of functional LWAs existing in the open literature within limited pages, only several selected functionalities are studied and detailed in this section for brevity, mainly focusing on disclosing their enabling technical features and underlying their design philosophies. During this studying process, the significance of the design formula depicted in Figure 5 will be particularly embodied and emphasized.

A. LOW SIDE-LOBE AND/OR LOW CROSS-POLARIZATION

For an LWA whose RDs are not altered along the length of the structure, no matter what the distribution type of the RDs is—continuously or discretely, the aperture amplitude distribution of such an LWA will follow an exponential decay function, as shown in Figure 4. Although there would be theoretically no side lobes for an infinitely-long aperture with such an amplitude distribution, it is not the case for a physically realizable LWA with a typical length of several wavelengths. In fact, the SLL will be high and is about −13−dB for typical non-tapered LWAs with a finite length [2], [130], which, obviously, is not good enough for practical system applications such as radars [132], [133]. In this case, perhaps the "low SLL" behavior is the most primitive functionality coming out of the mind of LWA designers; it is indeed the case when looking retrospectively into the leaky-wave history. To reduce the SLL, a specially tapered aperture amplitude distribution should be employed for LWAs. This requires tapering the RDs along the leaky structure in an orderly fashion to change the related distribution of attenuation constant α, according to the required design specification of SLL to be realized [2], [3].

The long-slot LWA shown in Figure 2(a) is simple in its configuration and easy to fabricate, and efforts have been continuously dedicated to developing and evolving it since

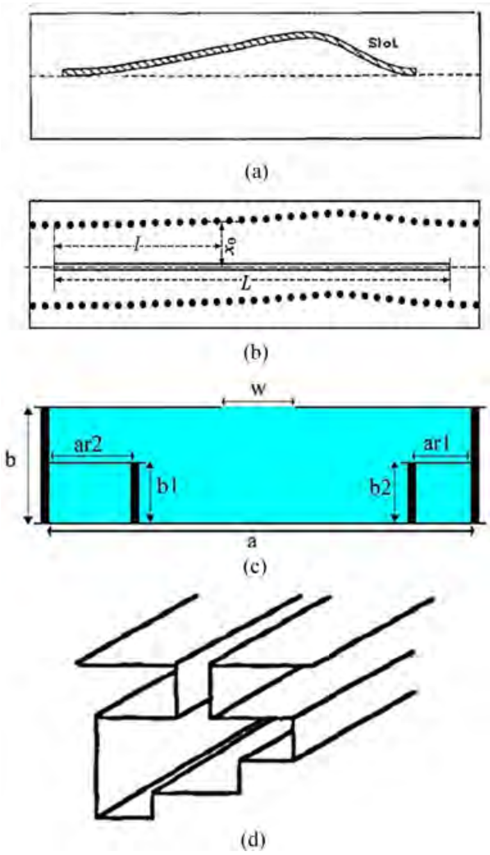

FIGURE 11. Several long slit/slot LWA examples with low SLL and/or low CPL. (a) RWG with a broad-wall meandering long-slot [18] (©1991 IEEE). (b) Meandering SIW with a straight long-slot [19] (©2011 IEEE). (c) Two-layered ridged SIW with a straight long-slot [71] (©2014 IEEE). (d) Stepped metallic waveguide with a straight long-slot [44] (©1997 IEEE). All these figures are reproduced with permission.

its inception [10], [17], [18], [19], [20], [22], [39], [40], [42], [43], [44], [46], [47], [57], [59], [60], [71], [72]. In addition to cutting a long slot on the sidewall of an RWG, the long slot can also be etched on the broad wall with apparent conveniences of fabrication and installation [18]. However, in each topology, if the slot is kept uniform along the structure, an SLL of about −13−dB will be unsurprisingly encountered as explained above. As a side note, the broad-wall long-slot LWA can be developed in a full-planar form [19] using the SIW technology, which owns the advantages of low cost, low profile, and ease of fabrication compared to its metallic counterpart in [18]. To taper the aperture amplitude distribution and thus reduce the SLL, the broad-wall long-slot can be meandered from the centerline to the sidewall and then backed, from the feeding end to the termination end, as shown in Figure 11(a) [18]. Such a meandering shape is determined by the required SLL and in turn the aperture distribution. Notably, although the SLL can be reduced using a meandering slot instead of a straight one, the LWA's CPL will be deteriorated due to the aperture asymmetry of the meandering slot [130]. Several studies were conducted to achieve a long-slot LWA with a low SLL while simultaneously maintaining a low CPL

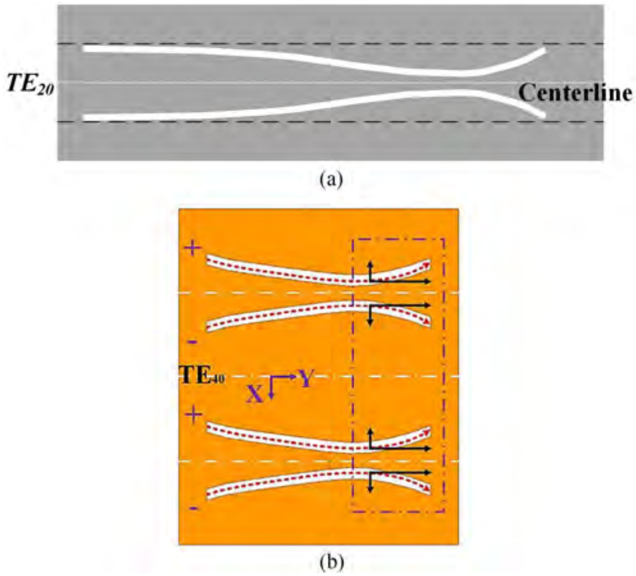

FIGURE 12. Higher-order-mode-based SIW/waveguide long-slot LWAs with both low SLL and low CPL. (a) TE_{20}-mode-SIW with a pair of meandering long-slots [20] (©2020 IEEE). (b) TE_{40}-mode-waveguide with two pairs of meandering long-slots [46] (©2020 IEEE). All these figures are reproduced with permission.

performance. They basically follow two technical routines. One of them is to use a centrally located, straight, and uniform long slot plus an asymmetrical waveguide or SIW [19], [42], [43], [44], [71], [72]. The symmetrical slot aperture is used for remaining a low CPL performance, while the asymmetrical waveguiding structure, which can provide asymmetrical modal fields, is responsible for realizing a tapered aperture illumination and thus low SLL. For example, a meandering SIW etched with a straight long slot, as shown in Figure 11(b), was proposed in [19] for this end. Similarly, a sinusoidally modulated empty (or air-filled) SIW etched with a straight long slot was proposed in [72]. Besides, embedded ridges or steps also work well in constructing asymmetrical metallic waveguides or SIWs to follow this technical thread [42], [43], [44], [71]. For instance, in [71], a two-layered ridged SIW long-slot LWA was presented as shown in Figure 11(c). By properly adjusting the widths of two different ridges inside the SIW while maintaining the slot aperture straight and uniform, a tapered aperture and thus low SLL, as well as low CPL, are achieved simultaneously. It is also the case in [42], [43], [44] where ridged or stepped metallic waveguides are employed, and one of them is depicted in Figure 11(d).

When referring to Figure 5, it is found that the above-mentioned technical considerations focus more on the "waveguiding structure" as opposed to the "RD"—only a single straight and symmetrical slot is used whereas various asymmetrical waveguiding structures are devised. In contrast, there is a complementary approach to realizing both low SLL and low CPL, with more emphasis on the "RD". Figure 12(a) describes a standard TE_{20}-mode SIW etched with a pair of meandering long slots [20]. In this topology, the two meandering slots present an even symmetry, and they are excited differentially by the SIW's odd-symmetrical TE_{20} modal fields. In addition to realizing the main goal of both low SLL and low CPL, this design scheme inherits several benefits from high-order-mode SIW, among which the merits of higher fabrication tolerance and larger footprint are suitable for high-frequency applications. Following this design thread, a TE_{40}-mode SIW with two pairs of meandering long slots was proposed in [46] for potential THz applications, as shown in Figure 12(b).

When we change RDs to modify the value of α, the value of β will also be changed in most cases since the two transmission parameters are coupled with each other. Thus, attention should be paid during the aperture tapering process in that the phase constant along the LWA should be kept unchanged to ensure that the radiation from each point or segment along the leaky aperture can be aligned in phase. If not, the phase errors introduced by a nonuniform phase constant distribution would spoil the designated SLL performance and distort the beam's shape (e.g., "shoulder" may be presented in the beam [18]). Therefore, more design considerations should be exploited for independent or flexible control of α and β. This normally requires a delicate implementation of both waveguiding structures and RDs, and a series of reported works can be found providing such merit. For example, the waveguide/SIW long-slot LWAs using ridges or steps [42], [43], [44], [71], as just described above, prove to be effective in this respect. This is also the case for the LWAs in [57], [58], [59], [60] that use the hybrid waveguide-printed circuit technology, or in [50], [74], [145], [146], [147], [148] that are implemented on the SIW or microstrip. In addition, the 3-D metallic SSPPs proposed in [93], [95] can also be exploited for this purpose thanks to their dispersion-insensitive characteristics when the lateral width of grooves is changed to adjust the radiation leakage. Interestingly, it should be noted that simultaneous and flexible control of the complex propagation constants will bring LWAs some other benefits or functionalities but not limited only to the typical design of low SLL radiation. For instance, LWAs with flat-topped/broadened radiation beams [95], near-field focusing/holographical pattern synthesis [146], [147], and spatially angular filtering response [148] can be easily realized if they possess such flexibly controllable complex propagation constants.

B. OPEN-STOPBAND SUPPRESSION

For a periodic structure, there is the appearance of a well-noted phenomenon called the "Bragg effect" when the electrical distance between adjacent periodic loadings is an integer number of half-guided-wavelengths [38]. This phenomenon is also called "lattice resonance" since a standing wave is formed along the periodic structure at relevant frequencies. What comes along with the "Bragg effect" or "lattice resonance" is that the waves propagating along the periodic structure are largely reflected back to the source and thus only little energy is injected into the periodic structure, thereby presenting a bandstop phenomenon. Because of this, periodic structures are sometimes used as "electromagnetic bandgap (EBG)" structures to design filters and reflectors in our RF/microwave regime [149], [150]; more details about this bandstop phenomenon will be given in Section III-D.

When a typical periodic LWA using the -1st-order space-harmonic is scanned at the broadside direction, the distance between adjacent RDs is just a guided wavelength at the relevant working frequency. In this case, a Bragg stopband is usually encountered, and it coincidently lies within the leaky-wave radiation frequency region of periodic LWAs. Such a stopband is mostly called the "open-stopband", where the word "open" refers to the fact that the periodic LWA is a radiative structure opened to the outside free space. If no special measures are considered to prevent the open-stopband effects, the periodic LWA will become "blind" or "nearsighted" when scanning at the broadside direction in a way that its radiation performances such as the gain and radiation efficiency get significantly deteriorated [2], [3]. Fortunately, many methods have been proposed to mitigate this problem. For example, a pair of identical RDs are introduced into a unit-cell, where the two elements are spaced by a quarter-guided-wavelength at the frequency corresponding to the broadside radiation [52]. This method is general and thus there are many different choices for RDs within the unit-cell—they can be stubs, strips, and slots, depending on the host waveguiding techniques used in constructing periodic LWAs. The working principle behind this is that the reflection caused by one of the two RDs can be canceled by the reflection resulting from the other, since a round-trip path will introduce a phase difference of 180° for the reflective waves from the two RDs at that frequency [150]. However, [52] states that there will be a residual stopband effect if the quarter-wavelength-spaced two RDs are totally identical since in this case, the two reflected waves from them are not the same in amplitude although they may be strictly out-of-phase. Recent research [151] suggests that if there is a slight dimensional difference between the two RDs together with a minor adjustment of their spacing, a complete open-stopband elimination can be made possible in practice, thanks to a perfect reflection-canceling mechanism. Comparatively, a more generalized solution based on impedance matching techniques (or the "matched unit-cell" concept) was proposed in [52], [53]. In detail, a delay line and quarter-wavelength impedance transformer or matching stubs are introduced in a microstrip comb-line LWA unit-cell to accomplish the required impedance matching at the broadside frequency point. Some other examples sharing such a similar principle can be found in [82], [85], [134]; they are implemented in the SIW technology and enabled by loading shorting vias. Note that there are other impedance matching techniques in our RF/microwave communities, such as T-, Π-, and L-shaped networks [150]; they also can be used to serve the same purpose. For example, to realize such a required "matched unit-cell" for open-stopband elimination or suppression, we may use a self-matched RD [62], which can be modeled as a T-shaped network. Another example is the simultaneous cutting of transverse and longitudinal slots in the broad-wall of an SIW LWA unit-cell [76], in which both slots are together modeled as an L-shaped network. By the way, the "reflection-canceling mechanism" using a pair of RDs described above can also be regarded as a manner of impedance matching according to the "small reflection theory" [150]. Several representative examples suppressing the open-stopband effects as described above are pictured in Figure 13. On the other hand, we can use another effective method based on the CRLH-TL principle to construct different kinds of open-stopband-suppressed LWAs [77], [78], [80], [108], [109], [110], [111], [112], which can provide a continuous beam-scanning from backward to forward direction through the broadside provided that the so-called "balanced condition" can be satisfied. Two typical balanced CRLH-related LWAs implemented on different host waveguiding structures (i.e., SIW and microstrip line) are depicted in Figures 14(a) and (b), with the dispersion diagrams of "unbalanced" and "balanced" cases exhibited in Figure 14(c).

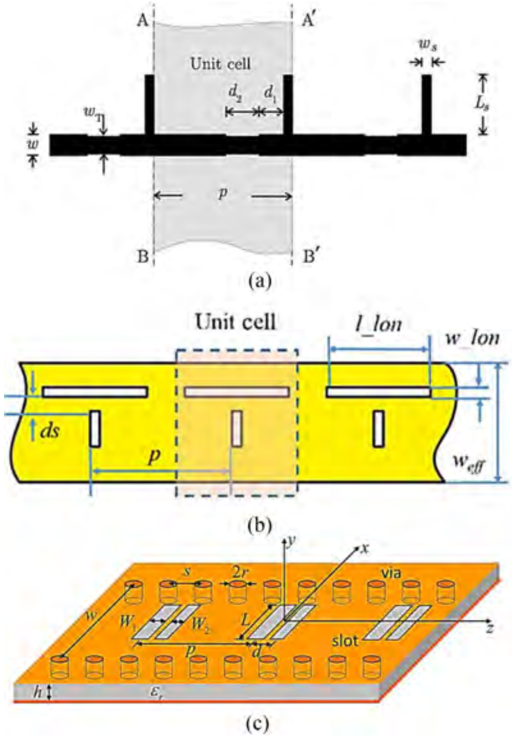

FIGURE 13. Typical approaches for open-stopband elimination or suppression following a generalized impedance matching mechanism. (a) Delay-line and quarter-wavelength impedance transformer [52] (©2009 IEEE). (b) L-shaped self-matching network constituted by SIW transverse and longitudinal slots [76] (©2016 IEEE). (c) Two slightly different RDs with a spacing of about a quarter-wavelength [151] (©2018 IEEE). All these figures are reproduced with permission.

C. RAPID BEAM-SCANNING

It is well-recognized that the distinctiveness of LWAs is mainly due to their frequency-enabled beam-scanning property. As the main-beam direction changes with frequency, several considerations may come up about the "beam-scanning quality" upon such logical thinking: how rapidly does the

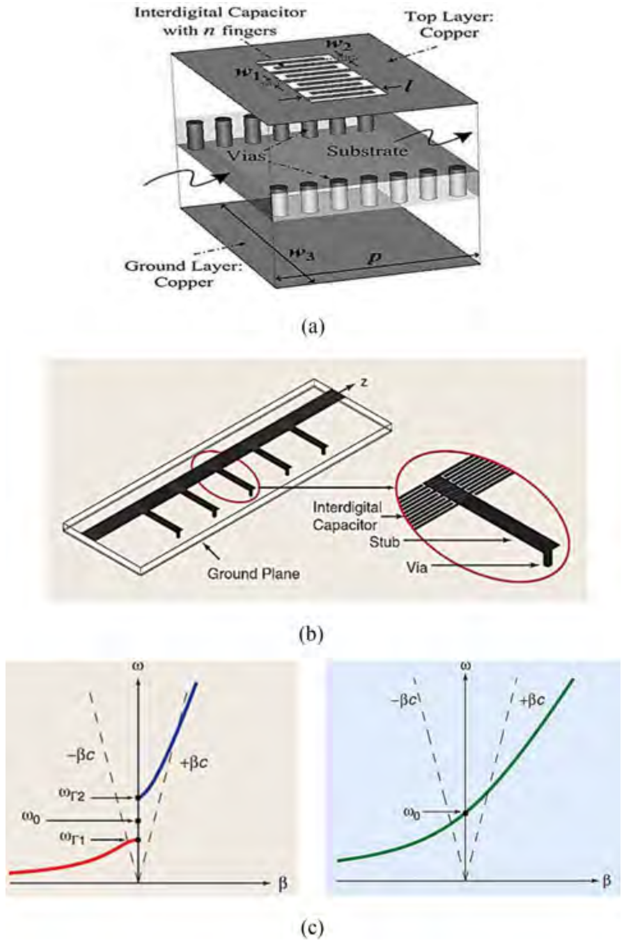

FIGURE 14. **Open-stopband suppression using CRLH-based TLs and principles. (a) SIW-based CRLH LWA [77] (©2011 IEEE). (b) Microstrip-line-based CRLH LWA [110] (©2004 IEEE). (c) Dispersion diagrams of unbalanced (left) and balanced (right) CRLH TLs [110] (©2004 IEEE). All these figures are reproduced with permission.**

beam scan with frequency? Can the beam scan very slowly (even not scan) or very rapidly as frequency changes? Can the beam scan linearly with frequency? In this subsection, we consider techniques dedicated to enhancing the beam-scanning rate for LWAs, and several enabling schemes [152], [153], [154], [155], [156], [157], [158], [159], [160], [161], [162], [163], [164], [165], [166], [167], [168], [169], [170] will be summarized and discussed.

To enable an LWA with rapid beam-scanning, the leaky mode should possess a phase constant (or normalized one) that changes swiftly with frequency, i.e., the phase constant has a large slope against frequency, as can be inferred from (1). To this end, there are mainly two considerations that we can follow and dig into—from either the "waveguiding structure" and/or the "RD", as seen from the construction formula of LWAs shown in Figure 5. Considering that the RD normally works as a perturbation on the host waveguiding structure, its role in influencing the leaky mode and thus the beam-scanning rate of LWAs might be secondary [2], [3]. Our emphasis, therefore, is mainly dedicated to the "waveguiding structure", which is easily understandable. Given this, perhaps the most direct approach coming to mind to steepening the phase constant of a leaky mode is to use a host waveguiding structure that possesses high media parameters (i.e., permittivity and permeability) or their effective counterparts. This is because in this case, the distributed inductance and/or capacitance per-unit-length along host waveguiding structures can be increased accordingly (and so does the phase constant's slope), according to the TL theory and from the perspective of the TL lumped circuit model [38], [150]. As such, any method that can equivalently increase that distributed inductance and/or capacitance per-unit-length of a TL may be used for the same purpose. This approach, interestingly, is in line with "slow-wave structures", which are a kind of specially designed periodic and equivalent TLs that possess larger effective inductance and/or capacitance per-unit-length than that of primitive TL counterparts they rely on [38], [150]. Notice that the so-called "slow-wave" term in slow-wave structures particularly refers to the fact that the relevant phase velocity of propagating waves becomes slower than its original counterpart due to some decelerating techniques taken on the primitive TLs as summarized in [125].

In general, several methods can be exploited to construct slow-wave structures, among which the "meandering" and "periodic loading" are typical [116], [117], [118], [119], [120], [121], [122], [123], [124], [125]. In this context, there is a natural technical scheme to design LWAs with rapid beam-scanning properties: use slow-wave TLs as the host waveguiding structures on which suitable RDs are added [152], [153], [154], [155], [156], [157], [158], [159], [160], [161]. Given this, the main technical issues of developing LWAs featuring rapid beam-scanning are converted to how to devise slow-wave TLs and how to conveniently load RDs on them. As a side note, CRLH TLs, as a kind of artificial or periodic waveguiding structures, have more dispersive features than their primitive/host RH TLs, especially in the LH frequency region [109], [110]. Thus, they may be properly used for realizing the desired rapid beam-scanning as reported in [169], [170]. Figures 15(a) and (b) depict two LWAs with rapid beam-scanning, and both rely on the "meandering" operation to construct slow-wave host TLs [152], [153], [154], [155], [156]. Comparatively, Figures 15(c) and (d) take advantage of sub-wavelength series-inductive and shunt-capacitive periodic loadings, respectively, to accomplish the construction of slow-wave host TLs [157], [158], [159], [160], [161]. In these examples, slow-wave host TLs and RDs have different responsibilities and roles in constructing LWAs: the slow-wave host TLs are just responsible for providing the leaky mode with a sharply changing phase constant, while the RDs such as slots and patches are merely devoted to making the host TLs opened and thus introducing radiation leakage. The role of RDs, however, is not limited to this, which can also be properly used to engineer the phase constant of the leaky mode just as in the situation of periodic loadings in constructing slow-wave TLs [162], [163], [164]. This is because RDs are normally resonant structures, as previously mentioned,

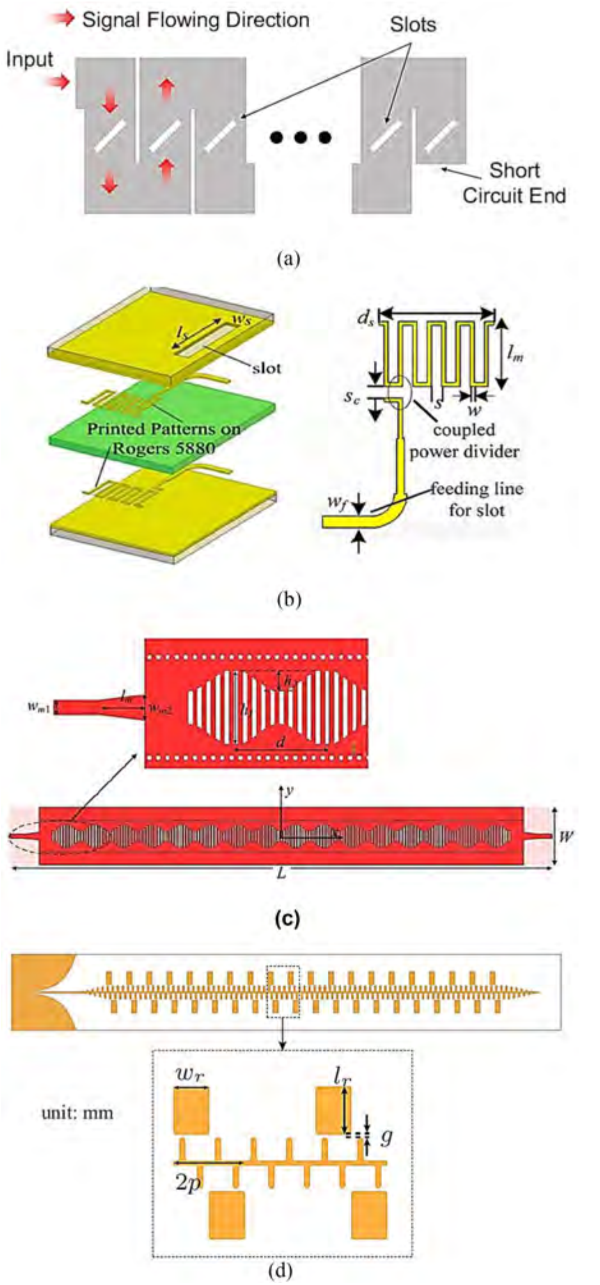

FIGURE 15. Representative examples of LWAs with rapid beam-scanning using different slow-wave TLs as the host waveguiding structures. (a) Meandering RWG [152] (©2009 IEEE). (b) Meandering stripline [154] (©2013 IEEE). (c) Series-loaded SIW [157] (©2018 IEEE). (d) Shunt-loaded (or corrugated) Goubau-line (SSPP) [161] (©2020 IEEE). All these figures are reproduced with permission.

and they also manifest inductive and/or capacitive properties over the frequency of interest. In [163], a quasi-uniform transversely slotted SIW with rapid beam-scanning behavior was proposed by taking advantage of the series inductive loading effects of transverse slots. In this example, the transverse slot is responsible not only for introducing radiation leakage but also for steepening the phase constant of the leaky mode. By the way, the role of RDs can also be extended to equip LWAs with the functionalities of "frequency-selectivity" and/or "radiation stability" as will be disclosed in Section III-E.

Recall that for most non-TEM TLs such as RWG/SIW and TEM TLs working in higher-order modes such as EH_1 microstrip-line, a cut-off phenomenon usually occurs because of the transverse resonance nature of propagating modes [4], [131]. In the frequency band just above and close to the cut-off (or stopband), the propagating mode normally behaves in a highly dispersive manner. This is also the case for a filter in which the passband edge that nears the cut-off presents a large dispersion, exhibiting a sharply changing group delay behavior. Because of the highly dispersive frequency zone close to the cut-off or stopband, no matter whether in waveguides or filters, this zone is usually abandoned for operation since signals would be seriously distorted if used. This is why, for example, the suggested frequency band of a standard RWG is ranged from 1.25 f_c to 1.9 f_c, where f_c denotes the cut-off frequency of the dominant TE_{10} mode [131]. However, this highly dispersive region close to the cut-off or stopband is just what we want to enable LWAs with rapid beam-scanning behavior. This is another technical point we want to summarize here [165], [166], [167], [168]. Figure 16 depicts two examples related to this. Close to the natural cut-off of a TE_{10}-mode RWG or EH_1-mode microstrip line, there is a fast-wave frequency region, which can be squeezed and narrowed by shifting another high-frequency stopband to a lower frequency. This additional high-frequency stopband can be created with the aid of high-impedance surfaces (HIS) [165] or periodic shorting vias [166], corresponding to Figures 16(a) and (c), respectively. In this case, a fast-wave passband is formed and the whole passband exhibits an enhanced dispersion behavior (i.e., steepened phase constant), as can be seen from Figures 16(b) and (d). It should be noted that the higher-frequency stopbands created in Figures 16(a) and (c) are due to different physical natures: the former is caused by the "element resonance" while the latter is by the "lattice resonance". More details about this will be expounded in the next subsection. When revisiting this rapid beam-scanning technique with reference to Figure 5, it can be found that it is more related to creating a special "waveguiding structure" that features a highly dispersive frequency region, which basically shares the same design logic as the abovementioned rapid beam-scanning techniques of using a slow-wave host TLs as well as the CRLH TLs. In conclusion, the property of rapid beam-scanning can be effectively realized for LWAs following those aforementioned technical schemes, upon which designing LWAs with additional functionality—"frequency-selectivity" is also feasible, as observed in Figures 16(b) and (d).

D. FREQUENCY-SELECTIVITY OR FILTERING CAPABILITY

As mentioned before, a natural fast-wave leaky mode normally occurs along with the cut-off phenomenon of host waveguiding structures, such as the well-known TE_{10}-mode long-slot RWG LWA and EH_1-mode microstrip-line LWA

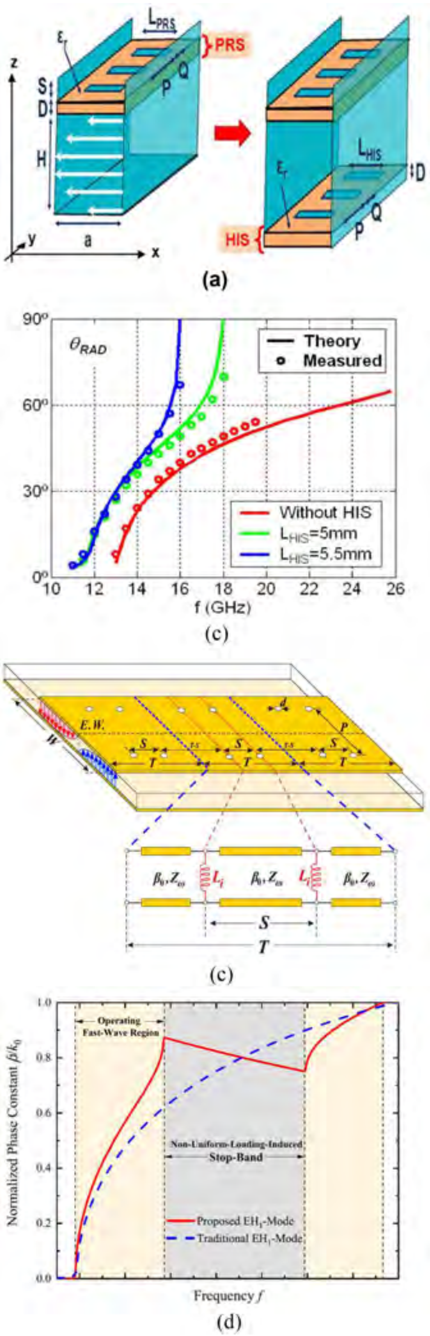

FIGURE 16. Representative examples of LWAs with rapid beam-scanning using a highly dispersive frequency region sandwiched by two bilateral bandstops. (a) HIS-loaded TE_{10}-mode RWG LWA and its related (b) beam-scanning behavior [165] (©2011 IEEE). (c) Pin-loaded EH_1-mode microstrip-line LWA and its related (d) normalized phase constant [166] (©2018 IEEE). All these figures are reproduced with permission.

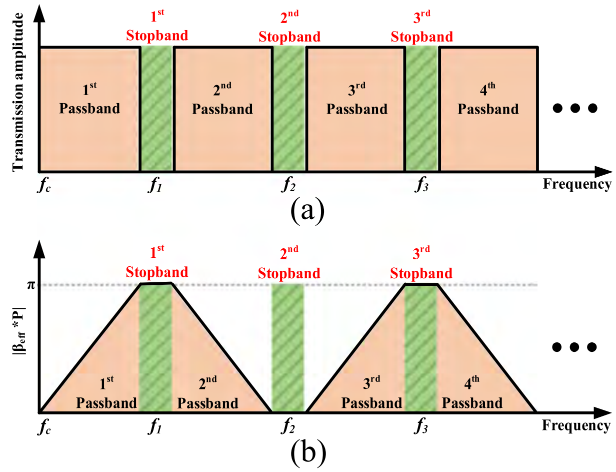

FIGURE 17. Simplified frequency responses of a 1-D infinite periodic structure. (a) Transmission amplitude. (b) Absolute phase delay of a unit-cell. Periodic bandgaps/bandstops caused by the Bragg resonance (lattice resonance) effects are displayed as greenish stripe regions. f_1, f_2, and f_3 are the center frequencies of the first three stopbands, in sequence. The bandstop phenomenon caused by loading's "element resonance" effects is not considered in this place, i.e., the loaded discontinuity is assumed to be non-resonant here. In (b), β_{eff} represents the phase constant of the propagating Bloch waves along the periodic structure, while P denotes the unit-cell period. The left initial point f_c on the transverse frequency axis may represent the cut-off frequency caused by the "transverse resonance", which is obviously zero for TEM/quasi-TEM TLs and non-zero for some non-TEM TLs (e.g., SIW or waveguide).

shown in Figure 2. Due to the "transverse resonance", both the TE_{10}-mode RWG and EH_1-mode microstrip-line possess high-pass filtering behaviors, and thus their relevant LWAs, loosely speaking, can be regarded as a kind of filtering LWAs (FLWAs). In this regard, the functionality "filtering capability" is spontaneously accompanied by those LWAs using the natural leaky mode, i.e., uniform LWAs. Nevertheless, we will show that this "filtering capability" is not exclusively embraced by uniform LWAs, while it is a general feature and is also possessed by space-harmonic-based LWAs such as quasi-uniform and periodic LWAs.

1). GENERAL FILTERING PHENOMENON IN LEAKY-WAVE ANTENNAS

In periodic structures involving quasi-uniform and periodic LWAs as well as some other periodically loaded TLs (e.g., slow-wave structures), periodic passbands/stopbands are usually encountered due to the "Bragg effect" [38]. It is a kind of resonance of the whole lattice (i.e., "lattice resonance") as mentioned before, which is completely different from the "transverse resonance" as mentioned above and the "element resonance" as will be described later. These passbands and stopbands in periodic structures respectively correspond to the non-resonance and resonance status of the whole lattice, which can be examined by the transmission amplitude and phase-delay behaviors as illustrated in Figures 17(a) and (b), respectively. The periodic stopband/bandstop phenomenon occurs when the lattice's period length is approximately equal to one or multiple half-guided-wavelengths, which approximately correspond to the center frequencies of the first or higher-order stopbands. Interestingly, when relating Figure 17 to quasi-uniform and periodic LWAs, we may conclude that the quasi-uniform LWAs work within the first passband, where the lower cut-off frequency f_c is determined by the natural cut-off ("transverse resonance") of the host TLs whereas the higher cut-off is defined by the first stopband introduced by the "lattice resonance". Comparatively, the working frequency band of periodic LWAs using the -1st-order space-harmonic is sandwiched between the 1st and 3rd stopbands, which are completely determined by the "lattice resonance". As already described in Section III-B, the 2nd stopband of periodic LWAs is referred to as an "open-stopband". On the other hand, Figure 17 is also applicable to uniform-type LWAs if one perceives that their periodicity of RDs is infinitesimal or zero. In this case, the related "first stopband" would be located in an infinitely high frequency, which actually means that no available "lattice resonance"-related stopbands are formed (because no physical periodic lattice exists in uniform LWAs). Note that the filtering passband of these classes of LWAs does not happen to coincide with their frequency bandwidth that performs beam-scanning, and thus the so-called "filtering" in this case may be strained to some extent. From the above statements, we may make some remarks: (i) LWAs, including uniform, quasi-uniform, and periodic types, are naturally accompanied by the functionality of frequency-selective or filtering behavior even though it is not so-well-noticeable or properly exploited; (ii) two kinds of stopbands characterized by different formation mechanisms can be found in those LWAs, where one is from the natural cut-off or "transverse resonance" of the host waveguiding structure while the other is due to the "lattice resonance" of the periodic configuration.

As described previously, in both quasi-uniform and periodic LWAs, RDs are normally resonant structures (e.g., slots, dipoles, and patches) and will be in a resonance state at specific frequencies. In that case, they may cut off the transmission path and cause large reflections to prevent the leaky mode from propagating, thereby producing an apparent bandstop phenomenon. This is the main reason that RDs in LWAs should avoid operating resonantly over the frequency band of leaky-wave radiation. Notably, this remark is also applicable to periodic-loading-based slow-wave structures and EBG-based low-pass filters if normal wave guidance and desired low-pass behaviors are required [120], [123], [124]. It is the so-called "element resonance" responsible for such a bandstop phenomenon. One of the most well-known examples exploiting this principle is the mushroom structure proposed in 1999 [171] where the "element resonance" introduces simultaneously both the stopband and artificial magnetic conductor (AMC) effects. The example shown in Figure 16(a) that makes use of the HIS to create a bandstop also belongs to this category as described in the last subsection. Moreover, the high-frequency cut-off (the so-called "plasma frequency") in a recently popularized TL, namely the SSPP, falls into this regime as well [129]. Notably, in this broad class of structures using "element resonance" to realize bandstop and/or AMC effects, their lattice distribution or periodicity is in a subwavelength regime. This means that the stopbands produced by the "lattice resonance" are far away from the frequency band of interest. In conclusion, it is seen that in addition to the "transverse resonance"- and "lattice resonance"-type

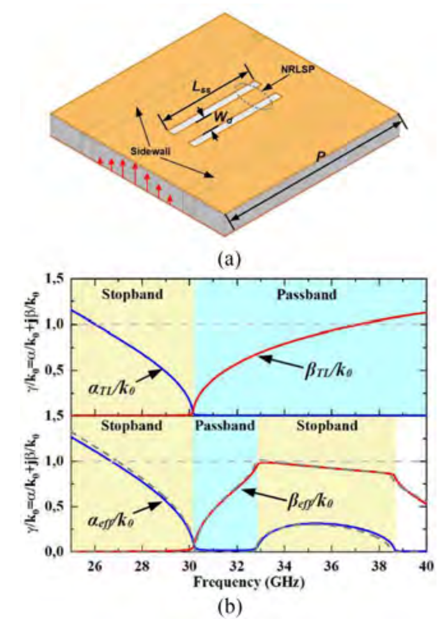

FIGURE 18. Bandpass filtering TL (or bandpass filter) based on periodically loaded SIW [167] (©2020 IEEE, reproduced with permission). (a) Unit-cell; (b) complex propagation constants (the upper half represents the counterparts of the primitive host SIW). The illustrated longitudinal slot-pair constitutes a non-radiative discontinuity. The other metal layer of the SIW can be used for implementing RDs (e.g., transverse slots) by which leaky-wave radiation occurs, thereby completing the design of an FLWA unit-cell.

bandstops, a third bandstop caused by RDs' "element resonance" also exists along with LWAs (quasi-uniform and periodic types) although it usually does not come into the frequency band of interest. Note that the three kinds of stopbands/bandstops apply to any periodic structure but are not merely limited to LWAs. Consequently, a class of FLWAs may be well developed by taking full advantage of the three kinds of stopbands/bandstops.

2). FILTERING LEAKY-WAVE ANTENNAS: CONSTRUCTION PRINCIPLES AND DESIGN CONSIDERATIONS

With reference to such three kinds of stopbands/bandstops and revisiting Figure 16, it is found that Figure 16(a) uses the RWG's natural cut-off of TE_{10} mode to form a lower stopband and the HIS's "element resonance" to produce a higher stopband, thereby establishing a filtering passband between them. Comparatively, Figure 16(c) uses the microstrip's natural cut-off of EH_1-mode for the lower stopband, and the "lattice resonance" brought by a periodic set of shorting pins for the higher stopband. Similar to the bandpass formation mechanism in Figure 16(c), Figure 18 depicts another example [167], which simultaneously uses the natural cut-off of an SIW and the first Bragg stopband introduced by periodic non-radiative longitudinal slot-pairs (i.e., closed discontinuity). Note that in this example, a set of additional transverse slots are etched on the opposite metal layer of SIW to deliberately introduce radiation leakage, thereby completing the

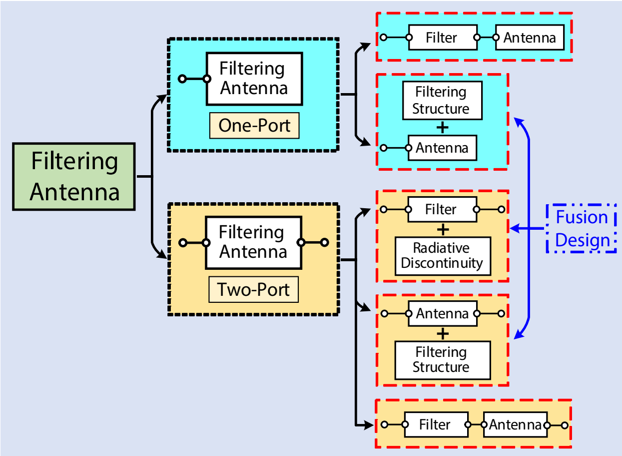

FIGURE 19. **A summary of various enabling techniques for two-port filtering antennas or FLWAs. Typical one-port filtering antenna techniques are also presented for comparison purposes.**

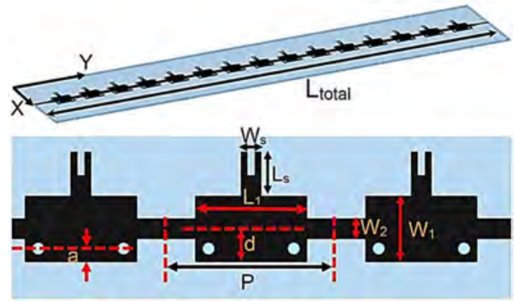

FIGURE 20. **A representative FLWA example where the filtering structures consisting of shorting vias and microstrip stubs are embedded into a two-port patch antenna unit-cell [178] (©2018 IEEE, reproduced with permission). This construction principle of FLWAs belongs to the second enabling technique of FLWAs in Figure 19.**

design of an FLWA. After taking a close look at the above-mentioned three examples, it can be found that (i) they all use periodically loaded TLs (the "secondhand" or 'derivative" TLs as named before) to work as a kind of host waveguiding techniques possessing filtering bandpass behaviors, based on which RDs are distributed continuously or discretely; (ii) the natural fast-wave frequency range (close to the natural cut-off due to the "transverse resonance") of these "secondhand" host TLs, which is somewhat perturbed due to periodic loadings and thus slightly deviated from that of the "primitive" TLs, is employed to construct leaky-wave radiation; (iii) the filtering passband is exactly the same as the fast-wave frequency range performing the beam-scanning. In a sense, these illustrated FLWA examples may fall into the "uniform" or "quasi-uniform" groups according to the construction formula in Figure 5 if the "secondhand" periodically loaded host TLs were perceived as a class of "equivalently primitive" host TLs possessing bandpass filtering characteristics (i.e., filtering TLs). As a side note, as revealed in Section III-C, an enhanced beam-scanning rate can be simultaneously realized along with the filtering capability for such FLWAs, i.e., multi-functionalities are obtained.

Consider the fact that our objective is to design and develop a broad class of FLWAs. As a general remark, most reported filtering antenna techniques in the open literature are particularly dedicated to one-port standing-wave (resonant-type) antennas like monopole, slot, and patch antennas rather than two-port traveling-wave antennas such as LWAs. Basically, those one-port filtering antennas follow the design principle of either replacing filters' final-stage resonators with antennas, directly cascading filters with antennas, or integrating filtering structures into antennas (a fusion design) [172], [173], [174], [175], [176]. Comparatively, to construct two-port filtering antennas or more specifically, FLWAs [177], there are basically three conceptual construction principles that evolve from those one-port counterparts, as described in Figure 19 where both one- and two-port enabling techniques for filtering antennas are shown. Among these techniques of FLWAs, the first is based on deliberately introducing RDs into pre-designed two-port filters, while the second one, as a complementary approach, depends on embedding filtering structures into pre-designed two-port antennas. In addition, we can also consider an approach of directly cascading an LWA (or unit-cell) with filters to establish an FLWA (or unit-cell). Notably, the first approach is interesting as it mainly lies in the recognition that filters are a kind of transmission-type components and thus can be perceived as a class of equivalent filtering TLs [38]. Based on this fact, we can use a set of cascaded filter unit-cells as the host filtering waveguiding structures to construct FLWAs in reference to Figure 5, provided that proper RDs can be easily created and implemented. Bear this in mind, it can be found that the examples in Figures 16 and 18 as well as the work in [168], all of which indeed use periodically loaded TLs as host bandpass filtering waveguiding structures, can be reasonably grouped into this enabling FLWA technique. This is also the case for CRLH-based LWAs since CRLH TLs are natural bandpass filtering TLs according to their circuit models [109], [110]. Certainly, some other sophisticated methods exist to develop filters in our RF/microwave communities [38], [150], which can be properly introduced to develop various kinds of FLWAs.

On the other hand, Figure 20 shows a typical example of FLWAs that belongs to the enabling technologies of "two-port antenna + filtering structure". It makes use of a two-port patch antenna incorporating microstrip stubs and shorting vias for filtering behavior control [178]. Note that the microstrip stub here acts as not only a filtering structure (i.e., a simple bandstop filter due to the stub's "element resonance") but also a radiator that may harmfully spoil the overall radiation performances of the proposed antenna. Following this thread but in reverse thinking, we may consider that there may be a two-port antenna that possesses natural filtering behaviors merely with recourse to its self-involved radiators, completely eliminating the need for additional practical filtering structures to accomplish the design of FLWAs (alternatively, we can imagine that there is a fictitious filtering structure inside).

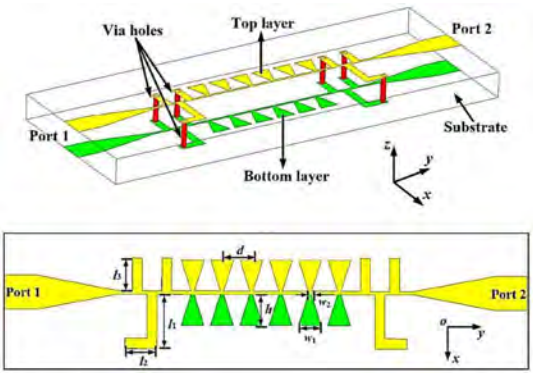

FIGURE 21. A representative FLWA example where two bandpass filters are placed at the two far-ends of a dipole-based LWA [180] (©2020 IEEE, reproduced with permission). This construction principle of FLWAs belongs to the third enabling technique of FLWAs in Figure 19.

Such a practical example, which depends on MMR-based RDs [179], will be discussed in the subsequent subsection "*Radiation Stability*". For classification purposes, we would still interpret this kind of formation mechanism of FLWAs as the second one shown in Figure 19. As a comparison, the example depicted in Figure 21 represents another kind of FLWA in which two bandpass filters are placed at the two ends of a dipole-based LWA [180]. This, apparently, belongs to the third approach of the two-port FLWA technique illustrated in Figure 19. However, no matter what kind of enabling techniques for FLWAs, two major points should be carefully considered:

i). The employed filters or filtering structures in FLWAs should have very little radiation loss or be completely free from it in an ideal situation, except for the case that the filters or filtering structures themselves are designed to contribute to desired radiation leakage. The main reason is that the radiation leakage per-unit-length of an LWA is normally small [2], [3], [4], [5], [6], [7], [8], [9]. Thus, we should prevent spurious radiation, which may be introduced by filters or filtering structures, from spoiling the intended radiation contributed by the designed RDs in LWAs.

ii). The frequency bandwidth performing beam-scanning in an FLWA should be the same as or wider than its designated filtering passband since only in this case the so-called "filtering" functionality does make sense. In a satisfactory case, the filtering passband should be exactly the same as the leaky-wave frequency range of beam-scanning.

E. RADIATION STABILITY

Fundamental antenna array theory tells that for an antenna aperture with a certain electrical length and amplitude distribution, its directivity exhibits an increasing trend when the radiation beam moves to the back-fire and/or end-fire directions from the broadside direction by changing the phase distribution of the aperture [130]. However, there are some more involved considerations about this aspect in LWAs, because the change of the phase distribution is enabled by altering the frequency, and thus, the effective electrical length of LWAs will certainly be changed as the beam is scanned with frequency [2], [3]. Furthermore, the aperture amplitude distribution of LWAs is normally changed with frequency as well (because the attenuation constant α of the leaky mode is generally frequency-dependent), whereas the RD's element pattern is even changed with both frequency and spatial angle. All of these frequency- and/or space-dependent factors mentioned above complicate the design of LWAs with radiation stabilities versus frequency, including the directivity, realized gain, radiation efficiency, beamwidth, and SLL. Recall that for an LWA, the phase constant determines the main-beam direction while the attenuation constant is directly related to the effective aperture length, aperture amplitude distribution, and radiation efficiency [2], [3]. Bear this fact in mind and look back to Figure 5, it can be inferred that some efforts should be made on "RD" rather than "waveguiding structure" if one wants to manipulate the attenuation constant and its associated radiation behaviors for LWAs (this is because the "waveguiding structure" is more related to the phase constant).

Perhaps the most relevant radiation property of an LWA with respect to the attenuation constant is the radiation efficiency as formulated in (2), according to which a stable frequency response of the attenuation constant should be obtained beforehand if one wants to realize an LWA possessing a stable radiation efficiency. To this end, there are mainly two approaches. Both rely on perceiving RDs as a kind of resonant structures and recognizing that the radiation ability of RDs is manifested by their resistance or conductance. Before detailing the two approaches, let's first examine the resonance characteristics of two kinds of RDs that are usually seen in LWAs, i.e., SMR- and MMR-based RDs, as already shown in Figure 9. For the SMR-based RD, there are two non-resonant frequency zones that can be exploited for leaky-wave operation, i.e., the frequency region before or after the strong resonance. However, they may present a totally reverse behavior of radiation efficiency for relevant LWAs. More specifically, the frequency region before the strong resonance presents an increasing trend of the real part of immittance. Resultantly, the relevant LWA's attenuation constant will increase with frequency, and thus so does the radiation efficiency according to (2). By contrast, the LWA's attenuation constant and radiation efficiency will decline with frequency if the frequency region after the RD's strong resonance is used for leaky-wave operation. Let's suppose a situation where the strong resonance depicted in Figure 9(a) is far from the targeted leaky frequency band. Although the RD's real part of immittance would therefore present a small value if so, it would desirably increase or decrease very slowly with frequency. In this case, we may realize an LWA whose radiation efficiency does not fluctuate heavily with frequency. This is the first approach that may effectually work. However, some drawbacks will follow using this approach: the length of the leaky aperture should be long

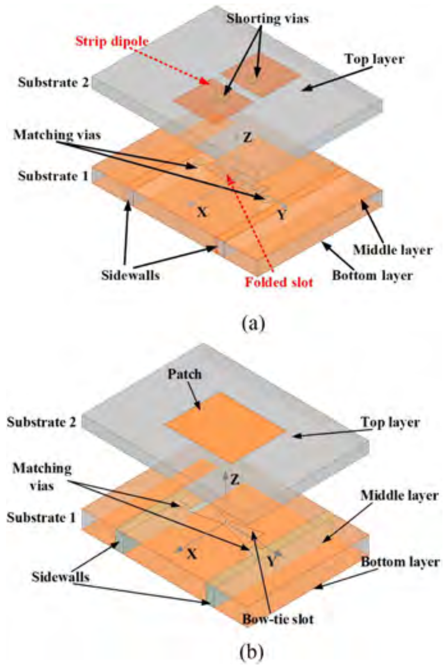

FIGURE 22. Two representative MSMMR-based RDs where different types of simple radiators are cooperatively used to construct a composite radiator exhibiting multi-resonance behavior [134] (©2020 IEEE, reproduced with permission). (a) Magnetoelectric dipole. (b) Aperture-coupled patch.

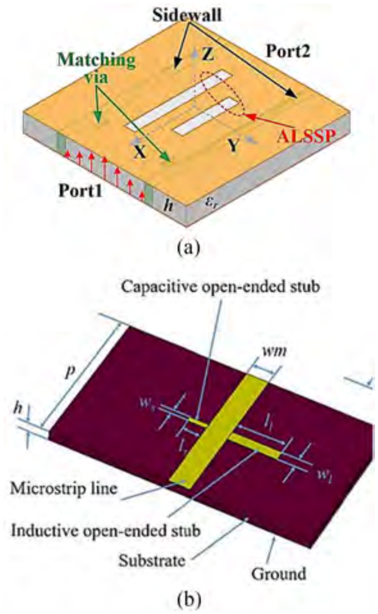

FIGURE 23. Two representative MSMMR-based RDs where the same type of simple radiators but with different dimensions are cooperatively used for creating multi-resonance behavior. (a) Slot-pair in SIW [179]. (b) Stub-pair in microstrip-line [50] (©2018 IEEE, reproduced with permission).

enough to make sure that most of the injected power can be radiated rather than being absorbed by the termination load.

After recognizing whether the stable radiation efficiency can be possessed by an LWA is basically related to its RD (strictly speaking, that is related to the frequency stability of the RD's real part of immittance), MMR-based RD can be naturally exploited for this purpose. Specifically, a triple-mode resonator characterized by two bilateral strong resonances and one central weak resonance is used. The frequency region reserved for the stable leaky-wave operation is sandwiched by such two strong resonances, as illustrated in Figure 9(b). Several examples following this MMR design principle, intentionally or unintentionally, have been proposed in [16], [50], [51], [134], [179], as shown in Figures 22-24. Notably, it is obvious that the issue of developing LWAs featuring a stable radiation efficiency is technically transferred to how to create MMR-based RDs on given host waveguiding structures. The special construction formula of LWAs shown in Figure 5 again comes into our vision. As shown in Figure 22, two typical well-known wideband multimode resonant antennas, i.e., magnetoelectric dipole and aperture-coupled patch antennas, are showcased here to work as MMR-related RDs for LWAs with radiation stabilities [134]. In contrast to the examples in Figure 22 where different types of simple radiators such as slot, dipole, and patch antennas cooperate in creating the required multimode behaviors, only one type of radiator (i.e., stubs [50] or slots [179]) but with different dimensions are used to create multiple resonances, as depicted in Figure 23.

On the other hand, note that resonance behaviors are always crystallized periodically over the frequency domain thanks to the periodic nature of time-harmonic electromagnetics and boundary conditions [38]. Because of this, a simple resonant structure, such as dipole, slot, stub, and patch, will possess several resonant modes over frequencies [130]. These multiple resonances may be simultaneously used for operations such as the design of multiband or wideband resonant antennas [130] as well as MMR-based LWAs[3] [16], [179]. As a consequence, in addition to using multiple structures to construct MMR-based RDs (i.e., MSMMR), one can also use a single structure for this purpose, i.e., SSMMR, as can be found in Figures 24(a) and (c), which take advantage of the first three resonances of a dipole [16] and open-ended microstrip stub [179], respectively. Figure 24(b) depicts the reflection coefficient of a bow-tie dipole, which is used as an RD to construct the LWA shown in Figure 24(a). The results suggest that the frequency band of stable leaky-wave operation is sandwiched by the first and third dipole-resonances (i.e., half-wavelength and one-and-half-wavelengths). This is also a similar case for the LWA employing the open-ended microstrip stub as the RD, as depicted in Figure 24(c). Here, it is necessary to mention that the developed MMR-based RDs should have coherent radiation behaviors when the resonance

[3]However, in most cases, only one of these resonant modes (usually the fundamental one) is used for operations because it is easier to manipulate only one mode at a time compared to the simultaneous control of multiple modes. This fact partially explains why most of resonant structures are usually under the treatment of an SMR in some typical applications like in LWAs. Nevertheless, multiple simple structures with each donating only one of its modes can also be combined to constitute a composite structure presenting MMR behaviors like what have been shown in Figures 22 and 23.

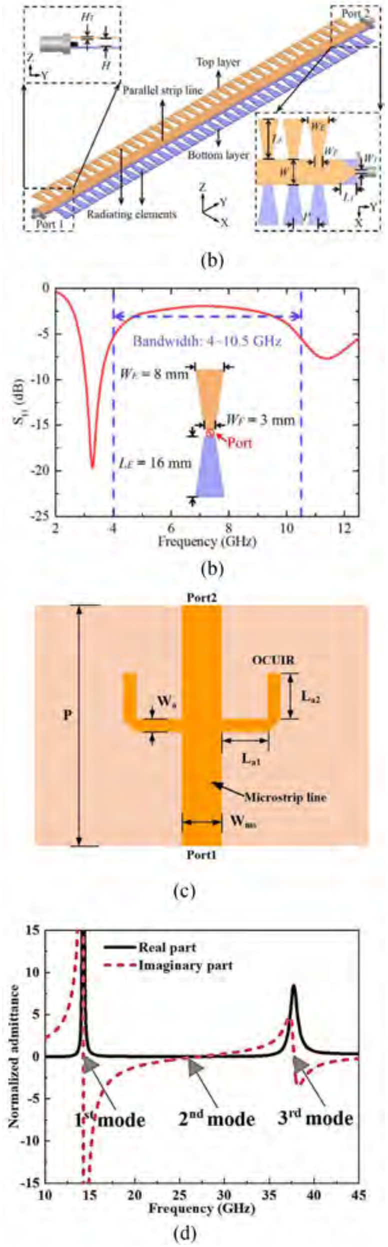

FIGURE 24. Two representative SSMMR-based RDs. (a) Dipole and (b) its relevant reflection coefficient [16] (©2019 IEEE, reproduced with permission). (c) Open-ended microstrip stub and (d) its normalized admittance [179].

status changes from one to the other over the frequencies of leaky-wave operation. Since three consecutive resonances of the RD are simultaneously used for such a development, all of the three modes should share the same polarization and similar radiation patterns. For example, the TM_{10} and TM_{01} modes of a rectangular patch antenna cannot be part of these modes of an MMR-based RD for LWA developments since they have different polarizations [130]. Meanwhile, since the TM_{20} mode of a rectangular patch antenna has a conical radiation pattern different from the broadside radiation possessed by the related TM_{10} mode, the two modes are also not suitable for developing such an MMR-related RD.

Before ending this subsection, we would like to point out that a stable attenuation constant enabled by the MMR principle can not only result in a stable radiation efficiency but lead to a frequency-independent aperture amplitude distribution. Note that mostly the SLL specification designated for a tapered LWA can only be realized at the design frequency point and/or its neighboring narrowband due to the frequency-dependent attenuation constant and resultant aperture amplitude distribution (all the examples and references involved in Section III-A are subject to this defect). Consequently, the MMR design methodology is very promising for aperture-tapered LWAs, because in this case the SLL may be kept unchanged with the beam scanned with frequency, i.e., wideband SLL performances. Nevertheless, to facilitate such a development, the MMR-based RD should better be capable of flexible mode-control [179]. This is easily understandable because by flexibly adjusting the two bilateral strong resonances of the RD, as shown in Figure 9(b), to be close to or far away from each other, the attenuation constant in the targeted frequency range can increase or decrease accordingly while still keeping its frequency stability. This may facilitate related LWAs to possess wideband tapered aperture amplitude distribution and thus SLL performances. On the other hand, recall that we have mentioned in Section III-D that the "element resonance" can be used for creating a bandstop phenomenon. The two bilateral strong resonances in an MMR-based RD will cut off the wave propagation along the leaky structure, thereby introducing two stopbands. For a periodic type LWA using MMR-based RDs, such two stopbands can be used for controlling filtering behaviors just like the example shown in Figure 20. Therefore, we may perceive MMR-based LWAs as a kind of FLWAs, which may be classified as the second enabling technique of FLWAs shown in Figure 19.

IV. SYSTEM-LEVEL APPLICATIONS OF LEAKY-WAVE ANTENNAS

To have prerequisite knowledge of various system-level applications of LWAs that will be reviewed later, let's first examine LWA-enabled frequency-scanning radars together with their competitors, i.e., mechanical and phased array radars, with respect to discussing their fundamental difference regarding the frequency-space domain characterization of radar operations [133], [181], [182], [183], as shown in Figure 25. For mechanical and phased array radars, a directive analog or digital beam with respect to its backend frequency-space domain coverage is plotted in Figure 25(a). Although this single narrow beam can be steered mechanically or electrically, it is normally kept fixed within the frequency bandwidth of the signal waveform (e.g., frequency-modulated continuous-wave or pulse [183]) when pointing towards a certain spatial angle. This signifies that the radar system can efficiently use the signal waveform's spectrums for further signal processing. By contrast, the relevant frequency-space domain coverage of an LWA-enabled radar solution is illustrated in Figure 25(b), suggesting that

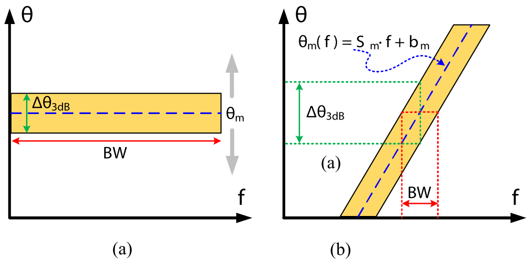

FIGURE 25. Simplified frequency-space domain characterization of radar operations with respect to different types of beam-scanning schemes [133], [181], [182]. (a) Traditional mechanical or phased beam-scanning using a wideband fixed-beam. (b) Frequency-enabled beam-scanning. Notably, the frequency-space domain in (a) usually represents an analog beam (i.e., analog beamforming) but can also stand for a digital beam produced by, for example, the digital beamforming of a full-digital phased array. The frequency-space domain in (b) assumes that the LWA has a linear beam-scanning function $\theta_m(f) = S_m \cdot f + b_m$, where S_m refers to the beam-scanning rate and b_m is a constant. A stable 3-dB beamwidth $\Delta\theta_{3dB}$ and gain that does not change with frequency are also assumed in (b).

available signal bandwidth BW for radar operation is determined by the 3-dB beamwidth $\Delta\theta_{3dB}$ and beam-scanning rate S_m of the LWA, which can be expressed as

$$BW = \frac{\Delta\theta_{3dB}}{S_m} \tag{5}$$

Eq. (5) tells that for an LWA with a certain beam-scanning rate S_m, its available spectrum bandwidth BW for the subsequent radar signal processing is linearly proportionate to its 3-dB beamwidth $\Delta\theta_{3dB}$. As a side note, when looking back at Figure 5 together with Section III-C and E, we can figure out that the beam-scanning rate is basically dominated by the host waveguides while the 3-dB beamwidth is closely related to the RDs. This means that there are multiple degrees of freedom for manipulating the available bandwidth of an LWA. Another direct remark observed from Figure 25(b) is that different passband spectrums would be transmitted or received towards different spatial angles for such an LWA-enabled system, i.e., spatially-dependent bandpass filtering behavior [184]. Specifically, if a wideband signal waveform is inputted into a transmitting LWA, different spectral components of the signal waveform would be emitted to different spatial locations. Comparatively, if an LWA is employed as a receiving antenna, it will output receivers with different spectral components that depend on the DoA of an incoming waveband signal waveform. This is the so-called "frequency-space mapping" or "spectral-spatial decomposition" property of LWAs, which is an alternative embodiment of the frequency-driven beam-scanning and constitutes the foundation for the DoA estimator [24], [184], [185], [186], [187], [188], [189], [190], [191] and microwave analog real-time spectrum analyzer [25], [192], [193]. Typical examples of such two application scenarios are shown in Figures 26(a) and (b), respectively.

It seems to be advisable if the LWA in Figures 26(a) and (b) has a narrow beamwidth and/or large beam-scanning rate, as this would bring the related system with a narrow available

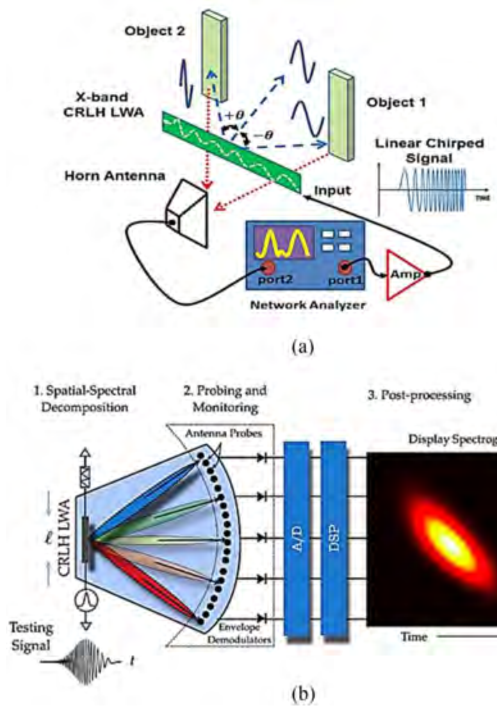

FIGURE 26. (a) DoA estimator [24] (©2015 IEEE). (b) Analog real-time spectrum analyzer [25] (©2009 IEEE). All these figures are reproduced with permission.

bandwidth according to (5), thereby leading to a better angle or frequency resolutions. Nevertheless, this is usually not a good idea for LWA-enabled frequency-scanning radars or tracking/imaging systems that require detecting and resolving both the range and angle parameters of multiple targets [35], [36], [194], [195], [196], [197], [198], [199], [200], [201], [202], [203], [204]. The reason for this is that the radar range resolution ΔR is inversely proportionate to the available bandwidth BW, i.e., $\Delta R = c/2BW$, where c is referred to as the light speed. This thus implies that either narrowing the beamwidth or increasing the beam-scanning rate of the LWA may shrink the available bandwidth and deteriorate the radar range resolution ΔR. In fact, there is a close relationship between the range and angle resolution in an LWA-enabled frequency-scanning system, which can be expressed as

$$\Delta R \cdot \Delta\theta = \frac{c}{2} S_m \tag{6}$$

where $\Delta\theta$ represents the angle resolution, which is also equivalent to the 3-dB beamwidth $\Delta\theta_{3dB}$ of the LWA [181], [182], [183]. The contradictory relationship between the two resolution metrics revealed in (6) should be carefully considered in radar applications. For example, how selecting the range and angle resolutions will determine the image pixel and in turn, influence the quality of the imaging system [199], [200], as shown in Figure 27(a). Therefore, a trade-off between the two resolution metrics is normally made in practice (note that improving the range and/or angle resolutions with advanced signal processing algorithms is beyond the scope of this article and thus is not considered herein).

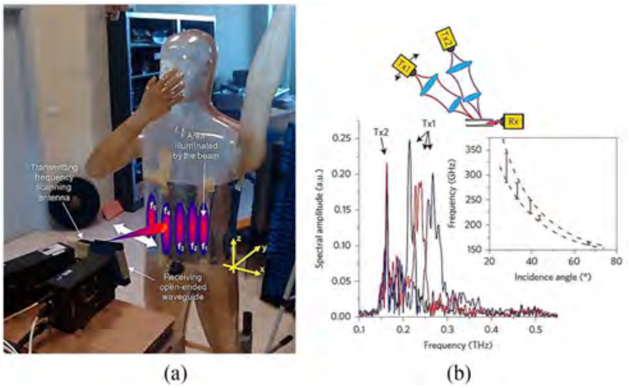

FIGURE 27. (a) Radar imaging [199] (©2013 IEEE, reproduced with permission). (b) Frequency-division multiplexing communication [34].

No matter what kind of LWA-enabled system applications, it is the natural frequency-enabled beam-scanning capability of LWAs that plays the dominant role in determining or defining system characteristics. In addition to the above-mentioned system-level applications, LWAs can also find potential in multi-target vital sign detection [205], [206] and duplexer/diplexer front-ends [207], [208]. However, it is not recommended to use an LWA-based front-end for wideband point-to-point communications because of its narrowband nature towards a specific spatial angle or user. Nevertheless, this property can be artfully exploited for FDM communications [34], [209], [210]. Typically, Figure 27(b) illustrates an example of this application scenario [34], which discloses the multiplexing process of terahertz signals from two transmitters that have different spatial angles with respect to the receiver. As a side note, an emerging book chapter that introduces and summarizes various LWA-enabled internet-of-thing (IoT) wireless networks including wireless power transfer, Wi-Fi, Bluetooth, etc. can be found in [211]; interesting readers may refer to it.

V. CONCLUSION AND FUTURE PERSPECTIVES

Such a long history of LWAs from 1940 to date has witnessed their four developing stages (see Figure 3), while this article is mainly dedicated to the third stage with focus on reviewing and summarizing several enabling concepts, structures, and techniques for the design and development of functional LWAs. To make this article more self-contained, we have also briefly presented several historic milestones of LWAs, described general principles and features of leaky waves, and exemplified some LWA-based system-level applications. Notably, comprehensive classification norms, which are made by dissecting LWAs regarding their general construction principle depicted in Figure 5, are presented as the ground-floor logic for appreciating different kinds of LWAs, and more importantly, pointing out the directions we can follow to come up with new solutions for prospective functional LWA engineering. An anatomical diagram describing and summarizing various classifications and functionalities of LWAs is already sketched in Figure 10. Because of limited space, we have merely reviewed several functionalities of LWAs in the open literature herein including low SLL and/or CPL, "open-stopband" suppression, rapid beam-scanning, filtering capability, and radiation stability. Most of these functionalities can be realized with recourse to making efforts in "waveguiding structure" and/or "RD", and this is the general design philosophy we want to highlight in this article. For example, by using periodically loaded slow-wave TLs as host waveguiding structures, we can design a class of LWAs featuring rapid beam-scanning behaviors. Similarly, EBG-type periodic TLs can be exploited as a kind of filtering TLs, by which we may devise a class of FLWAs. These examples are concerned with the "waveguiding structure", while we can also focus on the "RD" and design MMR-based LWA to realize radiation stabilities or even filtering capabilities. Moreover, both low SLL and CPL can be simultaneously realized for LWAs if the "waveguiding structure" and "RD" are considered concurrently, such as the TE_{20}-mode-based SIW etched with a meandering slot-pair.

Although newly invented functionalities of LWAs can be exploited for triggering new application scenarios, mostly those currently existent system applications stipulate what an LWA should better behave like. This remark is generally true for those functionalities we have presented in this article, and they are all prepared for typical system-level applications such as LWA-enabled radar, communication, and imaging/tracking systems. With the development of wireless technologies and the persistent pursuit of exploiting the frequency spectrum resources, our leaky-wave communities will continue to flourish through collective efforts worldwide. In this connection, there are several other promising functionalities or research directions, from the authors' perspective, that may be of significance for LWAs and particularly for their relevant systems, as follows.

A. LINEAR BEAM-SCANNING, AND STABLE RADIATION BEAMWIDTH AND GAIN

As demonstrated in Section IV, one has to tolerate the general narrowband nature of LWAs when benefiting from their simpler beam-scanning scheme (i.e., frequency-enabled) compared to the mechanical and phased counterparts. Even though such a narrowband nature (which can be interpreted, for example, as the range-angle-resolution dilemma in radar applications) could be well considered beforehand and accepted by system designers, the LWA should also present a linear beam-scanning function with frequency [168], together with stable gain and beamwidth performances as already assumed by Figure 25. This is to guarantee that towards any given spatial angle within the FoV, the LWA would present consistent bandpass filtering behaviors that have fixed absolute bandwidth. If so, the angle and range resolutions of related radar or tracking/imaging systems would not change with the DoAs of targets or incoming signals [35], [36], [194], [195], [196], [197], [198], [199], [200], [201], [202], [203], [204], while the related frequency-division multiplexing systems may provide equalized bandwidth for each communication channel [34], [209], [210]. Therefore, the invention of novel concepts, structures, or techniques aiming at the realization of LWAs with a linear beam-scanning, stable gain, or stable beamwidth is worth being systematically pursued and investigated.

B. WIDEBAND PERFORMANCE WITH REDUCED BEAM-SQUINTING EFFECTS OR EVEN FIXED-BEAM

Despite the narrowband of LWAs, it is actually referred to as the *radiation bandwidth* towards a spatial angle; they usually present a wide *impedance bandwidth* thanks to their traveling-wave nature. Suppose special concepts and techniques can be exploited to design LWAs with reduced beam-squinting effects or even with the radiation beam being fixed to a spatial angle over a wide bandwidth, i.e., low- or non-dispersive LWAs. In that case, we can realize a real "wideband" LWA in which both the impedance and radiation bandwidth are wideband [16], [29], [61], [103], [212], [213], [214], [215], [216], [217], [218], [219]. If so, those conventional standing-wave antenna arrays such as the series-fed patch or slotted SIW/waveguide antennas, which are typically used in radar systems (e.g., FMCW automotive radars) [130], [132], [133], could be superseded in practice by such wideband LWAs. This is mainly because standing-wave antenna arrays are generally born with a narrowband nature [130], which constitutes one of the major limiting factors that prevent relevant radars from using wideband signal bandwidth for good system performances [132], [133]. That is to say, wideband LWAs make modern radar systems that exploit wideband signal waveforms to realize improved detection performances possible. On the other hand, this kind of LWAs also can be deployed for wideband point-to-point communications such as the high-throughput backhaul transmission in 5G. As a side note, it would be more interesting and promising if the relevant beam's directional angle can be flexibly designed and tailorable since only in this case such wideband LWAs make significant benefits to modern system applications.

C. ELECTRICALLY SCANNED WIDEBAND LEAKY-WAVE ANTENNAS

In addition to those basic beam-scanning approaches described in this article (i.e., frequency-enabled, mechanical, and phased array), the "beam-switching" scheme, which traditionally makes use of beamforming/quasi-optical circuits and antennas to create a cluster of discrete beams with each being connected to an electric switch, also present an alternative to steer the beam [132], [133]. Note that a passive phased array radar using a phase-controlling circuit to conduct the beam-scanning can also be loosely perceived as a special kind of "beam-switching". Despite these beam-scanning schemes, recent years have witnessed an ever-growing research interest in electrically scanned LWAs [23], [26], [86], [104], [153], [220], [221], [222], [223], [224], [225], [226], [227], [228], [229]. Although the beam of such an LWA can be conveniently scanned at a fixed frequency with resort to electrically controlled varactors, P-I-N diodes, and exotic materials (e.g., liquid crystals and ferrites), the LWA's narrowband radiation performance is still suffered. This makes such electrically scanned LWAs somewhat short of practical significance in wideband systems. Therefore, it would be interesting and meaningful if electrically scanned wideband LWAs can be devised for modern radar/communication applications.

D. FUNCTIONAL 2-D LEAKY-WAVE ANTENNAS

As a class of line-source antennas, 1-D LWAs are typically characterized by a fan-shaped radiation beam, where a narrower beamwidth is formed in the scanning plane while a wider one in the transverse plane except that the transverse dimension is so large like Figure 7(b) that a narrow beam could also be radiated in this plane. Although a fan-shaped beam can be useful in surveillance and searching radars where a large space should be covered in the elevation plane, a pencil-like beam is also necessary for some scenarios such as high-precision target location/tracking and long-distance target illumination [132], [133]. In this case, 2-D LWAs are a simple and promising candidate solution to provide such a pencil beam compared to using large reflector antennas and complicated phased arrays. Also notice that a frequency-scanned conical radiation pattern of 2-D LWAs may help a lot in applications that need full-space coverage or illumination. As a natural extension of 1-D functional LWAs that are highlighted in this article, functional (or multifunctional) 2-D LWAs can be developed accordingly, which will be of significant interest to our communities. For example, 2-D LWAs designed with wideband and direction-controllable pencil-beam radiation (2-D scanning) will be practical in both radars and communications (e.g., 5G) [27], [28], [140], [143], [144]. Moreover, devising 2-D LWAs with various functionalities like electrical beam-scanning, Bessel beam generation, near-field focusing, holograph synthesis, and space-time-coding is also interesting and can be further advanced with resort to metasurface concepts [26], [30], [31], [32], [33]. Not to mention that some other functionalities involved in Figure 10 or techniques and concepts discussed in Section III can be applied as well to 2-D LWAs.

E. TERAHERTZ DEVELOPMENTS

Currently, the THz bands have become ever attractive in both academia and industry, and they have been assigned for high-quality radar sensing/imaging systems and future wireless systems such as the 6G communications. A huge spectrum resource in THz bands can be exploited to provide desirable system performances such as range resolution in radars and channel capacity in communications. However, for a phased array radar system working at THz frequencies, commercial phase-shifting devices are either unavailable or extremely expensive in the foreseeable future while the full-digital radar scheme is also unrealistic. In this case, the currently popular phased beam-scanning solution may lose its shine in THz radar applications. In contrast, some other beam-scanning solutions may take over from it in the radar world, among which the LWA-enabled frequency beam-scanning is a competitive candidate. Although the radar range resolution is impaired and insufficient in conventional low-frequency LWA-enabled radars as explained before, this resolution metric would be adequate in THz applications, thanks to the fact that the huge spectrum resource in such a high-frequency range makes the spectral bandwidth allocated to each spatial angle or user is sufficiently wide for high-quality radar operations. For the same reason, it is anticipated that future THz communication systems (e.g., 6G), or the joint design of communication and radar sensing systems, may also be well compatible with the frequency-enabled beam-scanning solution. Under such circumstances, comprehensive developments of THz LWAs [34], [46], [196], [198], [200], [201], [202], [209], [222], [230], [231], [232], [233], [234], [235], which act as a key enabling front-end component for THz wireless systems, should be well considered. As a side note, using the antenna-on-chip (AoC) technology can be particularly interesting and useful for relevant THz developments, such as CMOS-based on-chip THz LWAs proposed in [234], [235].

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